BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF MECHANICAL ENGINEERING
FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AEROSPACE ENGINEERING
LETECKÝ ÚSTAV

CALIBRATION TASK OF EXPERIMENTAL DEVICE FOR SPACE TECHNOLOGY TESTING
KALIBRACE EXPERIMENTÁLNÍHO ZAŘÍZENÍ PRO TESTOVÁNÍ KOSMICKÝCH TECHNOLOGIÍ

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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VEDOUCÍ PRÁCE

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Master's Thesis Assignment

Institut:	Institute of Aerospace Engineering
Student:	**Bc. Václav Lazar**
Degree programm:	Mechanical Engineering
Branch:	Aeronautical Traffic
Supervisor:	**Ing. Jakub Mašek**
Academic year:	2018/19

As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Calibration task of experimental device for space technology testing

Brief description:

Experimental testing facility for simulating extreme space conditions, such as the Mars atmosphere, was developed at the Institute of Aerospace Engineering, FSI, BUT Brno to test a space component: Heat Switch. A thermal conductivity measurement is carried out in the core of the thermo-vacuum chamber. However, the measurement of the samples is influenced by the heat losses and by the thermal contact resistances between the individual parts of the chamber.

Master's Thesis goals:

Calibration task of an experimental device for simulating Mars conditions and testing of the Heat Switch:

- Design a mathematical model of heat sources/transfers in the thermos-vacuum chamber
- Design a calibration task to define heat loss and thermal contact resistance coefficients
- Design calibration samples
- Measurement - determination of correction coefficients
- Compare the experimental results with the theoretical thermal model

Recommended bibliography:

MAŠEK, J.: Qualification Test of Heat Switch for Martian Conditions. Brno: Brno University of Technology, Faculty of Mechanical Engineering, 2016, 129 s. Master´s thesis. Vedoucí práce: Ing. Robert Popela, Ph.D.

Students are required to submit the thesis within the deadlines stated in the schedule of the academic year 2018/19.

In Brno, 25. 10. 2018

L. S.

doc. Ing. Jaroslav Juračka, Ph.D. Director of the Institute	doc. Ing. Jaroslav Katolický, Ph.D. FME dean

ABSTRAKT

Diplomová práce se zabývá možnosti kalibrace experimentálního testovacího zařízení. Zejména se věnuje návrhu termálního matematického modelu popisujícího tepelné procesy uvnitř zařízení v průběhu měření tepelné vodivosti vzorku.

První část práce je věnována seznámení se s testovacím zařízením, jeho limity a principem měření. Popisuje řešení třetí verze testovací komory, společně s nezbytnými úpravami, provedenými za účelem zajištění předepsaných simulačních podmínek. Zmiňuje také potřebu a důvody kalibrace.

Druhá část je především zaměřená na návrh kalibračních vzorků a termálního modelu. Uvádí definované požadavky a konečné vlastnosti vyrobených vzorků. Matematický model prezentuje postup výpočtu zjištěných tepelných ztrát a poukazuje na možnosti jejich zpřesnění.

Testování kalibračních vzorků bylo provedeno na nově zprovozněné třetí verzi testovací komory. Naměřené výsledky poslouží k ladění termálního modelu, nezbytného k dokončení kalibračního procesu, který umožní přikročení k další fázi testování v experimentální komoře.

ABSTRACT

The Master thesis deals with an experimental test facility calibration procedure. The thesis focuses on a complex mathematical thermal model proposal, which describes the inner facility thermal processes during the specimen conductance measurements.

The first section introduces the test facility, its limits, and the measurement principle. The necessary third version facility upgrades made to secure the prescribed test conditions are covered. The calibration need and reasons also resonate through the first section.

The second part aims at the calibration specimens and the Thermal Model designs proposals. The specimens requirements and their final properties are brought forward. The determined heat losses calculations are completed with the defined refining procedure suggestion.

The calibration specimens measurements were performed with a new test facility version three. The measured results will serve as calibration inputs for the Thermal Model tuning, necessary for the calibration task completion. The functional model will enable to proceed with the next phase of the test facility experiments.

KLÍČOVÁ SLOVA

Kalibrace testovacího zařízení, vesmírné aplikace, termoregulační vakuová testovací komora, testování, ESA, standardy, ověřovací metody, ověřování testováním, miniaturní tepelný spínač, přenos tepla, matematický model, kalibrační vzorek, přenos tepla vedením, tepelná vodivost, tepelný odpor, přenos tepla zářením, přenos tepla prouděním, tepelná izolace, Upilex, Mylar

KEYWORDS

Calibration of the test facility, deep space applications, baric vacuum test chamber, testing, ESA, standards, verification methods, verification by testing, miniaturized heat switch, heat transfer, mathematical model, calibration specimen, thermal conduction, thermal conductivity, thermal resistance, thermal radiation heat transfer, convective heat transfer, thermal insulation, Upilex, Mylar

BIBLIOGRAPHY

LAZAR, Václav. *Calibration task of experimental device for space technology testing* [online]. Brno, 2019 [cit. 2019-05-23]. Avilable: https://www.vutbr.cz/studenti/zav-prace/detail/117060. Master´s Thesis. Brno University of Technology, Faculty of Mechanical Engineering, Institute of Aerospace Engineering. Supervisor: Ing. Jakub Mašek.

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I would like to thank my master thesis supervisor, Ing. Jakub Mašek, for his professional guidance and support. I would like to acknowledge my thanks for his inspiration and the opportunity to be introduced to the project as well. My thanks further belong to the whole Institute of Aerospace Engineering project team for the kind and smooth cooperation during the past months.

DECLARATION OF AUTHENTICITY

I declare that the thesis entitled, “Calibration task of experimental device for space technology testing” is my own work and that all the sources that I have used or quoted have been listed and acknowledged at the end of the thesis.

In Brno on 23.5.2019 ……………………………………………………

Václav Lazar

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1 INTRODUCTION

An Early version of the experimental test device was built at the Institute of Aerospace Engineering, University of Technology in Brno in 2015. Deep space and Martian environment simulations inside of a Heat Switch Test Chamber allows testing space segment equipment. The subject of testing is a Miniaturized Heat Switch, originally designed by Arescosmo S.p.A. (formally Aero Sekur) in cooperation with ESA and provided to the Institute in order to perform the verification process – the Qualification test.

A Miniaturized Heat Switch (MHS) is space equipment with temperature-dependent variable conductance. Open and Close (Off/On) states change automatically, in a pre-set range with no external input power required. Such a temperature-driven unit is usually placed in between the thermally loaded device and the radiator as a part of the temperature control within the space segment element. The switch repeatedly opens and closes the conductive path, so the device´s hot interface is finally cooled down. The complete development at the MHS project was taken over by The Institute of Aerospace Engineering back in 2018.

Environmental tests performed inside of the Heat Switch Test Chamber (HST Chamber) should reveal the thermal conductance and functional range of the MHS functional specimens – BreadBoards (BB). However, the newly modified test device must be calibrated to proceed with the actual BB tests. The pressure subsystem of the HST Chamber recognized a significant upgrade in order to meet with the Qualification test requirements. Therefore, the definition of the operational procedures, test facility limitations, and measurement capabilities had to be established at the time of the initial system tests. HST Chamber Version 3 cleaning and completion were the necessary steps leading to the first experiments.

The calibration task itself was divided into particular phases, including the mentioned HST Chamber recovery, followed by the calibration dummy specimen proposal, production and measurements. For this purpose, it was required to design & manufacture a new generation of a dummy specimen intended for the adjusted 3rd version of the chamber. The outcome of the specimen experiments is the temperature difference between the measurement assembly layers – hot and cold sides, with the specimen placed in between these interfaces. Such a dummy position simulates future MHS utilization. Replacing the MHS is essential since the specimen’s conductance is designed in advance to mimic one of the switch´s states. Theoretically, the fact also enables the heat losses quantification, which should be determined in the Thermal Model. The complex Thermal Model should be a mathematical interpretation of the heat processes inside the HST Chamber. Although the calculations are possible, some of the variables would have to be assumed experimentally with respect to physical laws. Following the refining process would require multiple calibration specimen measurements results evaluation. The results should provide confident information about the behavior of the variables in the specific test conditions in order to describe the HST Chamber parameters.

The verification process is a long term and complex task. Understanding of the least phenomenon is the absolute key for the future application. The calibration must cover the solution for all the potential incidents which would occur during the testing. The Thermal Model hypotheses have to be in conformance with the actual measurements outputs to finally declare the variables assumptions are physically correct. This would be achieved only with patiently and precisely prepared tests which would confirm the overall correctness from the smallest steps. The MHS project should be concluded with the successful Qualification test campaign proofing the equipment suitability for the future flight applications. The calibration results have to provide great confidence about the inner processes knowledge to be able to confirm the outcomes of the measurement. Once the Thermal Model calculations are refined, it should become one of the primary tools of the Qualification test evaluation. With an HST Chamber calibration coefficients, derived based on the heat losses knowledge, the overall conductance determination process should be improved.

2 SPACE TECHNOLOGY TESTING

Space technology testing is one of the product verification methods. In general, verification can be achieved by one or more methods including test, analysis, review-of-design and inspection. Tests run under simulated mission-intended environments in order to evaluate the product performance, functionality and integrity. Verification by test helps to decrease project risks such as late discovery of design problems or in-orbit failures. Space system product verification is further described in ECSS-E-ST-10-02C Standard

Tests are run on the ground and should bring clear results of space segment performance. However simulating mission environmental conditions as encountered during its operational life cycle is necessary for majority of projects. Environmental tests cover natural and inducted environments. The test sequence and requirements should be established in the test program.

Testing itself is part of the system engineering process, and starts at an early phase of the mission when defining the verification process. The requirements for performing verification by testing of space segment system on the ground is scope the of ECSS-E-ST-10-03C standard. In general, space systems contains at least a space segment, ground segment or a launch segment. A space segment further integrates a space segment system, space segment element and space segment equipment. According to the mentioned standard, different approaches can be applied for space segment elements and space segment equipment testing. Therefore, a proper product identification should be held before the start of the test activity. Space system architecture can be observed in Figure 2.1. [1] [2]

A Space segment element is usually a payload, platform, orbiter or spacecraft as a whole. A space segment element can also integrate more embedded space segment elements (e.g. orbital module, descent module and service module in the case of Soyuz spacecraft). Elements are composed of space segment equipment.

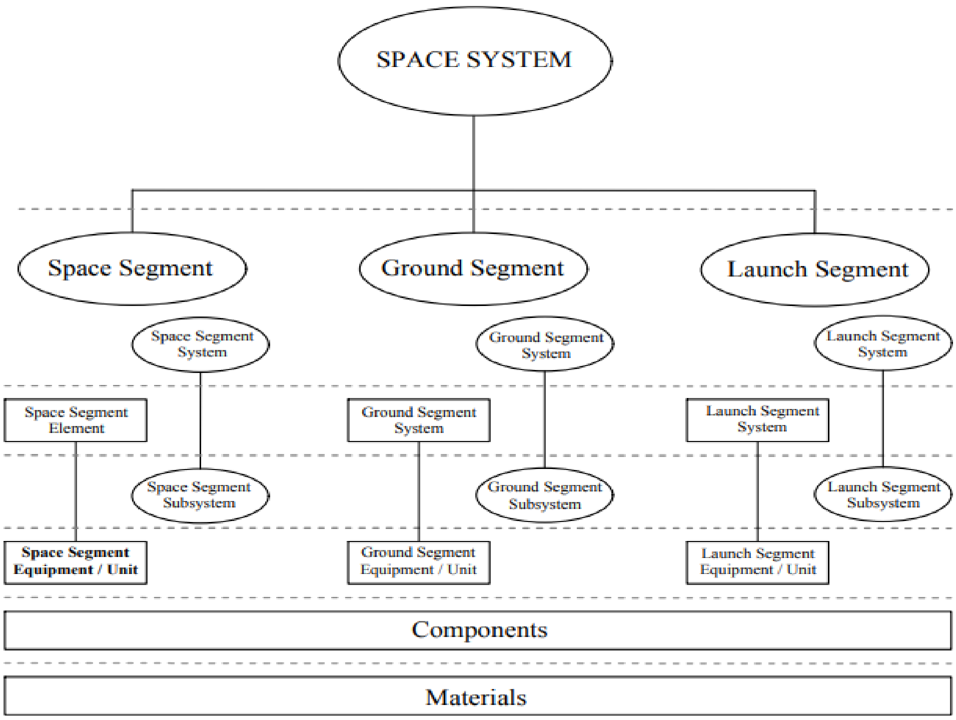

Figure 2.1: *The Space system breakdown.*

Space segment equipment is to be understood as an unit with a prescribed function. Equipment is further manufactured of components such as resistors, diode, solar cell or heat-pipe. The scale, integration and functionality of the product as well as mission scope and environment decides about test procedures and execution. The difference between the space segment equipment and space segment element can be observed in Figure 2.2.

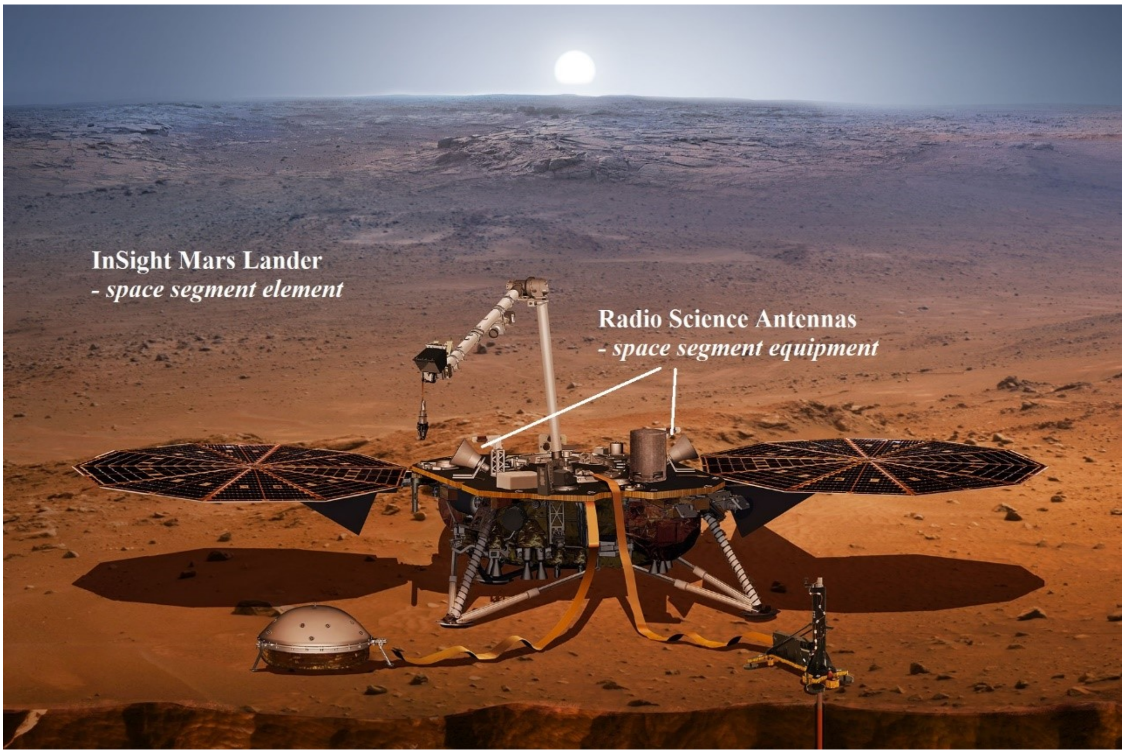

Figure 2.2: *The space segment element and space segment equipment examples. [3]*

2.1 Object of testing - Miniaturized Heat Switch

A Miniaturized Heat Switch (MHS) is a space segment equipment meant to be used in the landing payload for planet exploration or in deep space vehicles as a part of the heat management. Typical MHS installation is between the thermally loaded device and the radiator. The variable thermal conductance of the switch is temperature-driven, meaning the equipment does not require external power source. The Open & Closed states are switching automatically, based on the temperature applied to one of the Hot Interface or Cold Interface sides. [4] The schematic picture of the MHS can be observed in Figure 2.3.

The objective of the MHS project at the IAE BUT Brno is a MHS Qualification test composed of Environmental and Mechanical tests. The tests are to be performed with MHS representative BredBoard (BB) and Engineering Qualification Model (EQM) as a specimens.

The initial BB test results should define the EQM requirements. The tests should evaluate the specimen´s thermal conductance within variable simulation conditions. Conditions are simulated in the test facility, originally built for this purpose. However, the tests will be performed once the test facility calibration is done. The test facility calibration process is one of the focuses of this document.

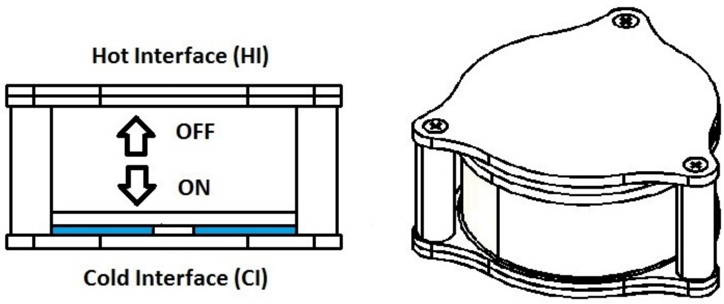

Figure 2.3: *The MHS functionality & design scheme.*

The Engineering Qualification model (EQM) tests are to be performed once Bread Board (BB) environmental test are evaluated. The project test structure is done in conformance with the test ECSS Test standard. Therefore applied test standard implementation is described further in this chapter.

2.2 Test program

Verification by testing can be done at different product development levels. However, a uniform coherent test program should be designed and agreed on. Testing in accordance with the test program is performed incrementally during established verification. The test program usually consists of test blocks which can be composed of one, or more tests grouped by discipline. The block definition is to be agreed on between the customer and the supplier (S&C) and depends on the tested product, therefore its application, mission purpose, complexity and integration. Product definition is essential, since space segment element can be treated as a space segment equipment after the S&C agreement. Usually, one test block covers full test program in the case of space segment equipment. Test blocks should be completed with formal reviews such as: [1]

- Test readiness review (TRR)
- Post test review (PTR)
- Test review board (TRB)

2.2.1 Test readiness review

A TRR should ensure, that all conditions allows to proceed with the test. Therefore, the TRR is to be held before the test activities stars.

2.2.2 Post test review

PTR formally declares test completion allowing the releasement of the tested item and test facility by breaking of the test configuration for further activity. Topics such as data verification and management; Assembly, integration and test plan (AITP) conformance and post test item configuration should be covered.

2.2.3 Test review board

TRB is a conclusion and a results review of a completed objective. Documentation, such as the test report, facility report, nonconformance report and list of procedure deviations should be presented.

Representatives of all involved parties, field specialists, project engineers and product assurance engineers should participate at the mentioned reviews. Specific requirements of the review attendance can be found in the standard.

2.2.4 Test documentation

The test program is completed with own test documentation. Each test program should be composed of Assembly, integration and test plan; Test specification; Test procedure and Test report. Particular documents should be available in different phases of product level. Each of the these documentation is to be established by the supplier.

Assembly, integration and test plan (AITP) also called “Test plan” at space segment equipment level should be derived from the product requirements, verification plan and verification control document. The document should be available for the TRR of the test program.

Test specification (TSPE) should be agreed on and available at the relevant test block TRR to allow test procedure preparation.

Test procedure (TPRO) is based on agreed TSPE and should be available at the relevant test block TRR as well.

Test report (TRPT) is complex document that concludes and describes test execution, procedures, results and deviations. TRPT should reflect relevant verification requirements and should be finished before TRB is held. [1]

2.3 Test conditions, tolerances & accuracies

2.3.1 Test conditions

Test conditions should be formulated by adding margins to intended mission environmental conditions. Margins can be set based on previous mission flight data, analytical prediction, relevant previous test results or by combination of the mentioned approaches. Test facility design, quality and safety management should be accepted by the customer. The final test configuration can´t damage the item under test, create hazardous conditions and cause any failures of the tested product.

In the MHS project, the test facility is represented by a Heat Switch Test (HST) Chamber capable of creating the required test conditions for BB/EQM experiments. The design of the chamber was accepted by the customer on 9 December 2015.

2.3.2 Test tolerances

The measured test values are to be compared with the specified requested values, reflecting the test error budges, originally agreed on by the customer before the test activity. Test tolerances are applied to the test value representing the allowable range within the measured parameters. Changes of the test tolerance margins in the project are possible. [1]

The MHS project relevant test tolerances are presented in table below. A list of all recommended tolerances of the test parameters can be seen in Appendix A1.

Table 2.1: *Test tolerances drafted from the ECSS Test standard*

Test parameters:	**Tolerances:**	
Temperature	Low	High
above 80 K	Tmin + 0/-4 K	Tmax -0/+4 K
T < 80 K	Tolerance to be defined case by case	
Pressure (in vacuum chamber)		
> 1,3 hPa	± 15 %	
$1{,}3 \cdot 10^{-3}$ hPa to 1,3 hPa	± 30 %	

< 1,3 · 10^{-3} hPa	± 80 %
Sinusoidal vibration	
Frequency (5 Hz to 2000 Hz)	± 2% (or +- 1 Hz whichever is greater)
Amplitude	± 10 %
Sweep rate (Oct/min)	± 5 %
Random vibration	
Amplitude	
20 Hz - 1000 HZ	-1 dB /+ 3 dB
1000 Hz – 2000 Hz	± 3 dB
Random overall g r.m.s.	± 10 %

2.3.3 Test accuracies

Initial instrumentations calibration needs to be done prior to defining the test accuracies. Those are further presented and agreed on in the test error budges along with the test tolerances before the test performance. Calibration procedures should be approved to verify the accuracy of the test instrumentation. The margins of the measurement accuracies can be defined according to the attached Table 2.2 or as at least one third of the tolerance of the variable to be measured. The accuracies definition is determinative for test instrumentations responsible for the test execution. [1]

Accuracy and tolerance requirements were initially formulated in the MHS project by Aero Sekur. However, calibration results, as well as test accuracies and conditions will be established before each test.

Table 2.2: *ECSS Standardized MHS project relevant Test Accuracies.*

Test parameters:	**Accuracy:**
Temperature	
Above 80 K	± 2 K
T < 80 K	Accuracy to be defined case by case
Pressure (in vacuum chamber)	
> 1.3 hPa	± 15 %
1.3 · 10^{-3} hPa to 1.3 hPa	± 30 %
< 1.3 · 10^{-3} hPa	± 80 %

Tables 2.1 & 2.2 presents allowable tolerances & accuracies for temperature, pressure and vibration tests in conformance with the European space standard. However, whenever a stricter tolerances & accuracies were agreed on within the MHS project, they should be considered as mandatory. For not specified tolerances and accuracies in the MHS project, standard ones are to be used.

Only the MHS project relevant test accuracies are presented in Table 2.2. Official standard recommendations can be observed in Appendix A1.

2.4 Space segment equipment testing

The test requirement and therefore the test baseline and organization can vary depending on the product categorization. Space segment equipment and space segment element test requirements are in general different. Since the MHS is considered to be space segment equipment, it´s test approach is further described. A more detailed categorization recognizes space segment equipment types which are presented in categories. The tested product can be considered to fit one or more of these types according to its functionality and technology used. Space segment equipment test requirements are than a combination of all fitting type requirements. [1]

Types of space segment equipment: antenna; battery, valve; thruster; thermal equipment; optical equipment; mechanism; solar array and solar panel.

The final MHS classification, test baseline and implementation is further described in *2.4 MHS relevant test selection & implementation.*

2.4.1 Test sequence:

- Performance test (PT) at the beginning of the test program *
- Full functional test (FFT) at the end of the test program *
- Reduced Functional Test (RFT) after each environmental test block, before / after transportation

*Both PT and FFT should be performed under ambient conditions, with identical results within the test tolerances.

The performance tests results should be in accordance with the performance specification and should verify the space segment equipment under specified environment. FFT verifies the complete function of the item under the test, in all operational modes. Both tests can be combined and executed as a single test as well. PT, FFT or RFT tests should be also performed during the thermal tests or if the operational environment changes.

With the test facility already built, prior calibration of this device needs to be held before a qualification test runs. Therefore, the mentioned test sequence will be applied once the test facility is calibrated. However, the calibration approach itself requires testing of the HST chamber performance, using representative specimens. Calibration tests should reveal whether the HST chamber is capable of creating required conditions and whether it allows to test the agreed MHS properties and performance.

2.5 MHS relevant test selection & implementation

The Qualification test (QT) is the objective of MHS project at the IAE BUT Brno. However, Calibration tests needs to be performed prior the actual QT. The calibration test results should declare Qualification test input parameters and test procedure knowledge. The actual HST Chamber measurements are executed within defined test design, presented in chapter *4.6 Test design.*

2.5.1 General test conditions

General test requirements were specified for the QT phase. The actual test design should respect such a defined requirements. Measurement accuracies and requirement define the minimal test facility performance demands as well.

Environmental conditions:

Vacuum:	vacuum pressure	$1 \cdot 10^{-5}$	[mbar]
Mars environment:	CO_2 gas pressure:	8 – 10	[mbar]

	overall theoretical pressure:	$1 \cdot 10^{-5} - 10$	[mbar]
Mars atmosphere temperature:	Unknown, should be established during the HST chamber systems experiments		

Ambient test conditions:

Ambient temperature:	22 +/- 3	[°C]
Ambient pressure:	1013.25 +/- 33.3	[mbar]
Relative humidity:	55 +/- 10	[%]

General measurement tolerances and accuracies:

Temperature:	Max. limits:	-0 °C, +3 °C
	Min. limits:	-0 °C, -3 °C
	Time stability:	+/- 1 °C
	Geometrical uniformity:	+/- 3 °C
Thermocouples accuracy:		+/- 0.5 °C
Pressure:		+/- 5 %
Test duration time:		+ 5 %

Equipment accuracy

Calibration margins should be established during the initial Calibration test phase.

***Note**: Project agreed tolerances & accuracies are stricter than the Standard values.*

2.5.2 Calibration test phase

Calibration tests should evaluate the HST Chamber performance, general data evaluation and chamber accuracy. The tests are to be executed prior to the Qualification test using MHS representative specimens with exactly known properties and BB.

The test procedures and execution should also be established during the CT for further implementation within QT. While the test accuracies and tolerances remain the same in both cases, the test sequence and test selection is different. CT phase is further presented in this thesis along with specimen selection, test execution description and measurement evaluation. The performed tests are not drafted from the ECSS Test standard.

Calibration Tests:

Facility systems tests:	Pressure tests
	Thermal tests
	Environmental tests
Specimen tests:	Thermal tests
	Cycle Block I tests

2.5.3 Qualification test phase

To define Qualification test requirements baseline in the MHS project, two factors had to be considered. One of the factors is space segment equipment type, which decides about specific test execution (e.g. Thermal ambient test). The other factor depends on an agreement between

C&S, i.e. a set of the tests agreed to be performed by the supplier. IAE BUT is responsible for performing both MHS environmental and mechanical Qualification tests.

Qualification Tests:

General	FFT/RFT
Mechanical	Physical properties
	Random vibration
	Sinusoidal vibration
Thermal tests (environmental)	Thermal vacuum
	Thermal ambient

The Calibration & Qualification HST Chamber measurements are always in conformance with the one of the agreed Test Blocks, further presented in chapter *4.6 Test design*.

3 EXPERIMENTAL TEST FACILITY

BB and EQM tests are to be performed in a special facility manufactured by IAE in order to fulfil this task. The facility is a baric chamber operating in vacuum, which enables to simulate Mars atmosphere and outer space conditions. The rest of the test chamber characteristic (specifications) were derived by Aero Sekur´s and ESA´s Preliminary Functional Specification of MHS (ESA SOW Heat Switch − Preliminary Functional Specification Report) and Requirement Document TN02 310609 A. Other specific requirements were put together after initial inspection of the early version of the test chamber. These requirements combined previous specifications with operational knowledge gained during the first versions testing. Construction demands were not determined in any document. However the test facility has to be able to simulate the intended mission environment and verify EQM. [4]

3.1 Test chamber requirements

General requirements for the test chamber design are associated with its purpose specifically to be able to simulate various conditions. The design of the chamber should allow to vary both Hot and Cold Interface temperature, in different configurations, imitate the heat radiator outside in the ambient environment by controlling Cold Interface temperature and simultaneously simulate the equipment power dissipation in the specified range. [3]

Some more requirements are specified for the Hot and Cold Interfaces since each interface has different tasks to fulfil:

The Hot Interface: copper plate mounted on the top of the opposite side to the Heat Switch hot interface can simulate controlled cooling and heating:

- Allow heating on most of the surface in range: - 55 °C ÷ + 60 °C.
- Simulate the unit thermal dissipation by local heating of the area from 0 W to 10 W.

The Cold Interface: in order to simulate cooling a radiator another copper plate was chosen to be used. The cold Interface has to allow to regulate, or to keep constant temperature in specified range using liquid nitrogen and heating device.

- Range of the temperature -125 °C ÷ + 50 °C.

The mechanical connection of the Miniaturized Heat Switch on the satellite panel is simulated by mechanically coupled Cold Iterface and thermal plate. This connection will also limit the direct conductivity from the hot interface and heat sink.

Heaters should be independently regulated by separated power supplies. The accuracy of the HI heater should be within 0.1 W.

Temperature distribution on both interfaces will be measured by thermocouples which will also control the heater circuit. A completely independent thermal environment has to be performed on both Hot and Cold Interfaces.

Other general requirements can be derived from the ESA SOW Report [5] which is divided into 3 main groups of specific related requirements. These groups are: End Product Definition, Specifications and Subsystem requirements. Specifications include a list of requirements for the Heat Switch such as: Functional & Performance, Interface, Environmental, Physical & Resource, Operational, Design and Verification & Testing. Some of the performance, environmental, verification and testing conditions are mandatory for the test chamber design since the test facility has to be able to perform operational conditions for proper verification of the Heat Switch. Demands specified by ESA are presented in the tables and the additional notes specified by Aero Sekur are presented below the related table. All of the ESA and Aero Sekur requirements are identified by its own reference number. Requirements related to test chamber design are listed below: [4] [5]

Interface Requirements

Spec Reference	Description
IR 3	The Heat Switch should meet the requirements with cold interface temperatures between -125 °C and 50 °C and with hot interface temperatures between -55 °C and 60 °C.

Environmental Requirements

Spec Reference	Description
ER1	The qualification temperatures for the Heat Switch are the temperature listed in IR3 with a margin of 10 K applied on the extreme values (-135 °C and +70 °C).

Verification & Testing Requirements

Spec Reference	Description
VTR 1	The Heat Switch should be a subject to 8 thermal cycles over the temperature range specified in ER1 with a hold-time of 1hour at each temperature extreme.
VTR 4	The thermal performance of the Heat Switch should be measured.
VTR 5	The simulation of large heat load variations should be performed (i.e. by increasing and decreasing the applied heat load).

3.2 Later defined requirements [4]

After an inspection of the Heat Switch Test chamber on 9 December 2015, representatives of the interested institutions accepted the facility design with additional requirements originally published in the final Meeting report 15-GB-010. Chamber relevant modifications and procedures have been applied since Version 2 design.

Relevant changes of the chamber design, systems and test plans stated in the Meeting report are mentioned below:

- $1 \cdot 10^{-5}$ mbar pressure environment inside the test chamber during EQM testing. It could be reached with a high vacuum pump.
- Freezing of CO_2 during the tests caused pressure drops, therefore temperature applied on CI was limited to − 110 °C. (original requirement was − 125 °C)
- Application of a thin graphite foil between hot interfaces and switch contact surfaces in order to increase the thermal contact conductance. Six temperature

- measuring probes will be installed on the switch hot side, another two probes on the upper heating interface to determine whether the conductance was increased.
- Additional insulation of the switch that would reduce thermal exchange from the specimen to the chamber is needed. Mylar VDA and Upilex films are to be applied around the switch. Another Upilex film will protect inner Hot and Cold Interfaces from heat leakages.
- Unlike in the previous versions of the chamber systems, DC relays will be used.
- Initial calibration runs for the BB testing are to be done with two dummy specimens. One of the specimen will simulate open case conductivity, the second one will be with close conductivity.

3.3 Chamber design development description

The final chamber design is based on the previous versions designed and built at the Institute of Aerospace Engineering, BUT between years 2014 – 2016. The chamber was firstly manufactured in 2015 following particular requirements stated in the ESA SOW and TN02 Report documents. Three early versions of the test facility (Version 1, Version 2 initial, Version 2 advanced) were developed for BreadBoard testing procedures. Because of the involvement of the additional copper plates, some components had to be modified or changed during the development process of initial Version 2. The initial Version 2 can be observed in Figure 3.1.

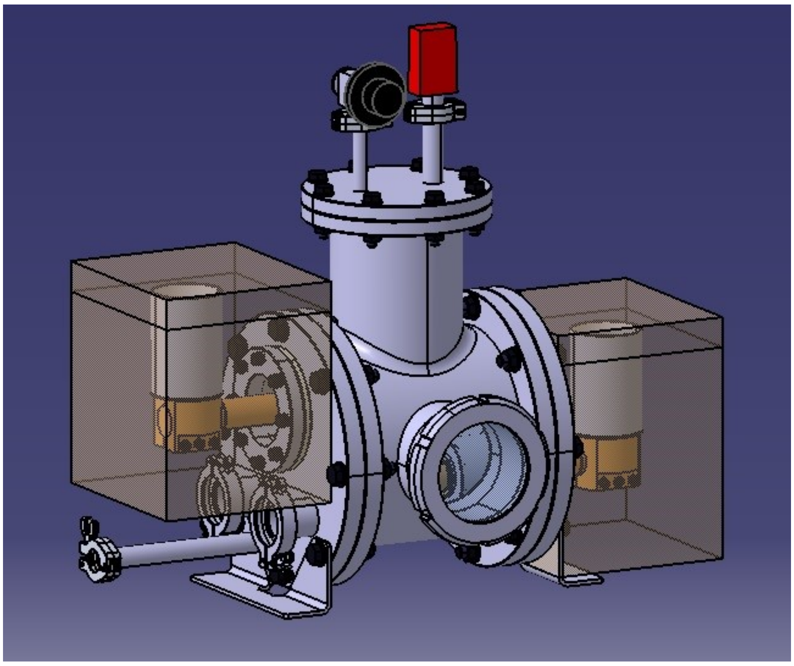

Figure 3.1: *HST Chamber Version 2 Initial. [1]*

Due to wrong temperature indication of Version 2 int., another upgrades were made to finally come up with Version 2 advanced. These modification included a three-wire line configuration of temperature probes, change of the pressure gauge with vacuum valve for better pressure indication and other components remake. [4]

3.4 Heat Switch Test Chamber Version 3

Current Version 3 design is meant to run the EQM tests of the Miniaturized Heat Switch once the test facility Version 3 is calibrated for such a task. In general, the requirements are slightly rigorous than for BB testing meaning another modification is needed. The transmission from Version 2 advanced to Version 3 include two significant changes.

- Two additional vacuum feed-through on CI side flange, maximum of 16 thermocouples can be installed
- Pressure of $3{\cdot}10^{-5}$ mbar during the EQM test

That resulted one of the flanges has been modified to have a new hole for electric vacuum feed-trough installation that enabled to have up to 16 temperature sensors in overall. This solution should bring more detailed temperature indication.

Lower pressure of $3{\cdot}10^{-5}$ mbar inside the test chamber during the Miniaturized heat switch EQM test should secure the maximum conductance level of the heat switch in an optimistic case. A brand new vacuum pump was ordered and installed to the chamber system in order to reach the intended pressure.

3.4.1 Heat switch test chamber design

The heat switch test chamber is a test facility build to meet all general requirements and therefore to be able to perform the intended mission environment, considering possible future modification for a proper evaluation of the miniaturized heat switch.

The body made out of stainless steel houses all the necessary components and equipment for Miniaturized Heat switch testing. The central uniform part of the body is T shaped enclosed with two side and one top flanges along with a front inspection window. The side flanges are designed as an interface between the outer temperature control & support & measuring systems and the inner MHS test systems. This exchange is possible thanks to four vacuum electric feed-throughs, gauges and valves installed in the flanges. Unlike in previous Version 2, two additional vacuum feed-troughs were added to cold side Flange B. Follow the Figure 3.2 to observe described components.

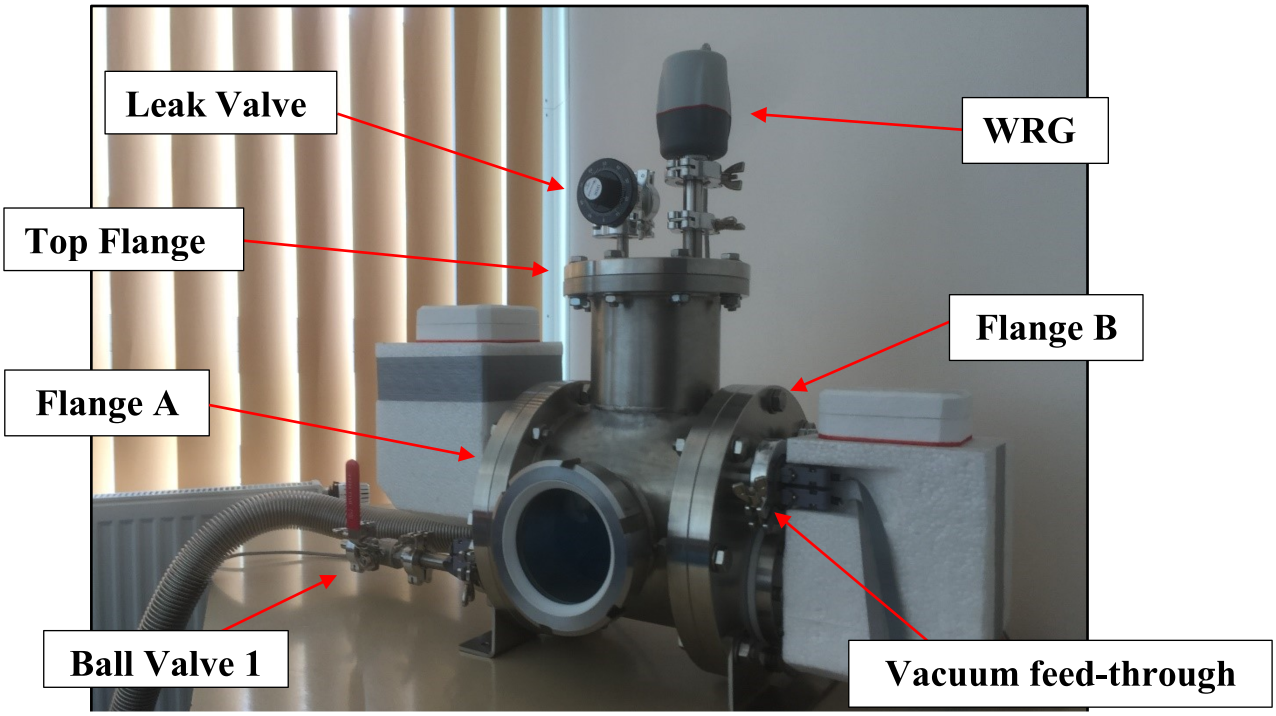

Figure 3.2: *HST Chamber Version 3.*

The hot side flange Flange A is completed with a Ball Valve 1 placed on the connection rod. The valve enables hermetically close the chamber or to connect other components. Both Flange A vacuum feed-troughs are used for temperature data transmission.

A Leak valve and Wide Range Gauge (WGR) are placed at the top flange. The Leak is an connection to the CO_2 supply system. WRG is the ultimate gauge capable of measuring low pressures with high accuracy.

The top part of the chamber also houses weight mass which increases the pressure necessary for better contact conditions between HI and CI surfaces. Removing the top flange allows to access the inside of the chamber for specimens exchange or manipulation.

The inspection window (at the front) is easily removable as well. Opening the front window is necessary for any specimen manipulation. However it serves for eye control of inner status and composition during the tests too.

HI and CI tanks are used as a storage of liquid nitrogen (LIN) which was chosen as a coolant. To prevent high thermal leakages from HI and CI tanks insulations made of blocks of PU foam have been applied since Version 1 chamber design. The tanks are fastened with copper clamps to copper rods allowing connection and heat transfer from the tanks to the inner interfaces. The HI heat transfer assembly is slightly different from the CI heat transfer assembly since the configuration has to allow heat dilatation of the thermally loaded components. Therefore, the connection of the copper rod and the inner Hot Interface is realized with four copper belts fastened by eight copper screws instead of direct connection as in the CI heat transfer assembly case.

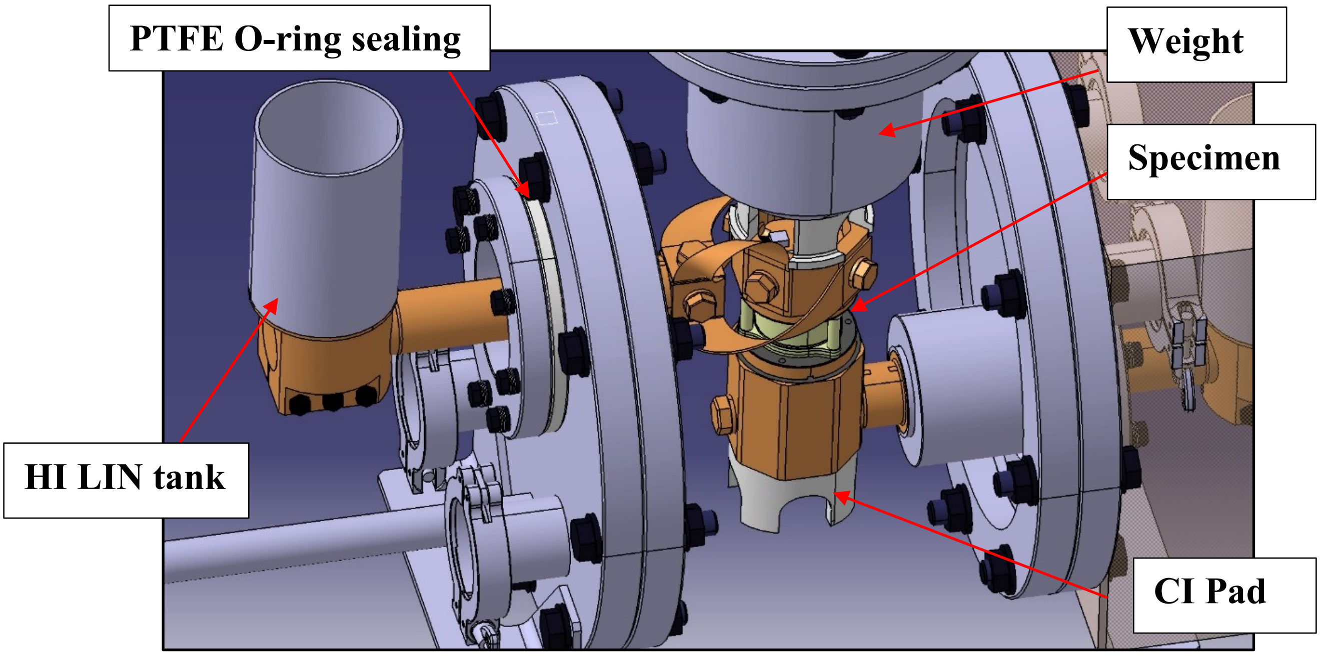

Figure 3.3: *Inner HST Chamber Version 3 assembly. The main T-shaped body and HI LIN tank insulation are hidden.*

The specimen position is in between the inner Hot and Cold Interfaces inside the test chamber. This placement represents future application of the MHS. A specimen is pushed to interfaces by weight placed at the top of HI assembly on PTFE pad. The pad also insulates thermally loaded interface from the weight. Another pad is installed bellow the CI to increase the stability of the inner assembly and can be observed along with whole inner assembly in Figure 3.3.

According to the final Meeting report 15-BG-010 a graphite foil has been added to specimen-interface contact surfaces to increase thermal contact conductance. Also Upilex and Mylar foils were applied as an insulation material around the specimen and heat transfer assembly components.

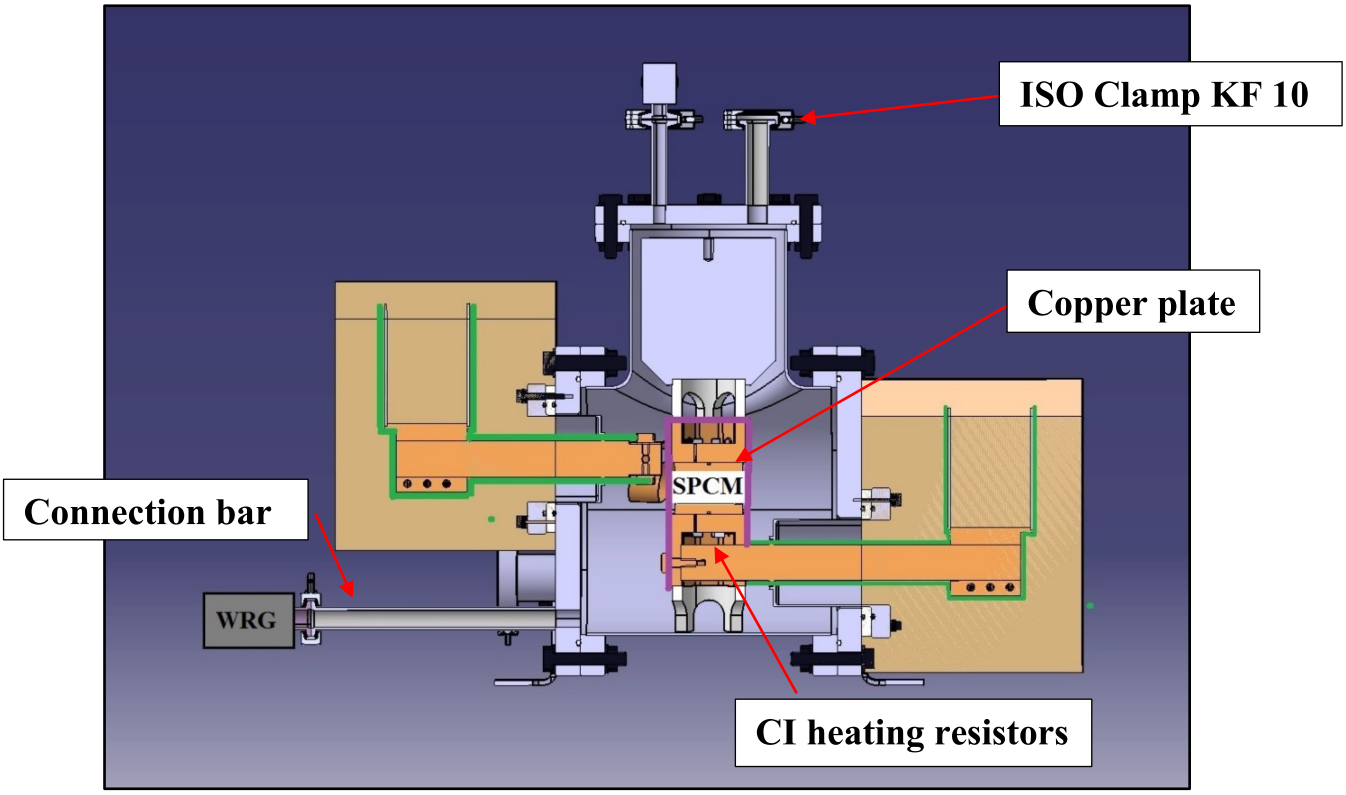

Figure 3.4: *HST Chamber Version 3 cross section. The green boardings indicates PTFE tape insulation. Purple areas represents the Upilex foam and Mylar & Upilex film insulation.*

Thermal leakages of the test chamber are further minimalized due to application of PTFE tape to all copper components as well. A minimum of 10 layers was applied so the final thickness of PTFE coverage should be at least 2 mm. Storage tanks and some other stainless steel parts exposed to low temperatures were insulated in the same way.

The green color in the Figure 3.4 indicates the PTFE tape usage, while the purple boarding defines the areas with multi-layer thermal insulation.

3.4.2 Final HST Chamber Version 3 design parameters

Physical parameters:	Height:	393 mm (509 mm with systems connection)
	Width:	344 mm
	Length:	530 mm (713 mm with systems connection)
	Inner volume:	5.5 dm^3
	Mass weight:	~ 55 kg

Materials used:	Stainless steel:	main body construction, flanges, weight, LIN tanks
	Copper:	thermally loaded parts such as CI / HI heat transfer assembly, inner CI / HI & plates, HI contact belts, screws fastening copper parts
	Teflon (PTFE)	insulation of MHS, LIN tanks and all copper components, CI pad, Weight pad, o ring sealings
	Other	rubber sealings, glass, glue

3.4.3 Test chamber V3 systems

Three main supply systems are necessary for creating purposed environment. Both temperature and pressure parameters has to be controlled and regulated during all the tests. Third, CO_2 supply system is implemented for simulating Martian conditions tests. Each of these supply systems are composed of several components such as valves, gauges and indicators further described below.

Separated data acquisition system (DAS) is used as a collector of measured data signals allowing to display intended data through PC is a part of the V3 test chamber systems as well.

Temperature control system

A wide range of temperatures needs to be simulated inside of the chamber. Therefore, temperature control system has to allow heating, cooling as well as measuring of temperature.

Heating subsystem: allows automatical heat control thanks to two separated Temperature controllers (for Hot and Cold Interfaces) and to DC relays. Depending on the dominant input signals from the Temperature controller DC relays enable to regulate the amount of the electric power provided to four heating resistors. Temperature controllers can regulate temperature based on required manually set temperature, or automatically according to prescribed program. List of all components used in heating subsystem:

- DC power supply (HI: DPS-3005D 30V/5A, Zhaoxin; CI: ProfiLine 3524, McVoice)
- DC relay (CRYDOM D4D07)
- Temperature controllers (Ht40P – TE-K0R-000)
- Resistors (R 8R TO220 35W, 1% HITANO)
- Amperemeter & Voltmeter

Cooling subsystem: with respect to environment and interface requirements, cooling system is necessary to reach intended cryogenic temperatures. Liquid nitrogen (LIN: − 196 °C) was chosen as a coolant which is able to cool down inner interfaces down to – 125 °C after adding into HI and CI tanks. The cooling of the Interfaces is indirect and is possible thanks to the copper heat transfer path from the hot and cold interface tanks to the inner Interfaces. LIN has to be stored in specially insulated tank with automatic overpressure control. Cooling system assembly:

- Liquid nitrogen (LIN: −196 °C)
- LIN storage tank

Temperature measuring subsystem: measured electric data signal is transferred from the temperature probes through the electric vacuum feed-throughs to the temperature controllers (for reference) and to the DAS unit. Platinum thermal resistors (temperature probes) are placed on different surfaces. Six probes are glued in each copper plate of the specimen, another two probes are on the inner Hot and Cold interface. The final temperature measuring and data signal transfer assembly then consists of 16 probes, with three-wire line configuration and three electric vacuum feed-throughs. Three-wire line helps to increase temperature measurement accuracy by better resistance measurement since the unwanted wire resistance is measured and eliminated.

Temperature measuring subsystem components are than listed below:

- Electric vacuum feed-throughs (D-sub 2x9 pin; KF40)
- Temperature probes (Pt 100: P0K1-202-3FW)

Temperature probes layout inside of the assembly can be further observed in following Figure 3.5.

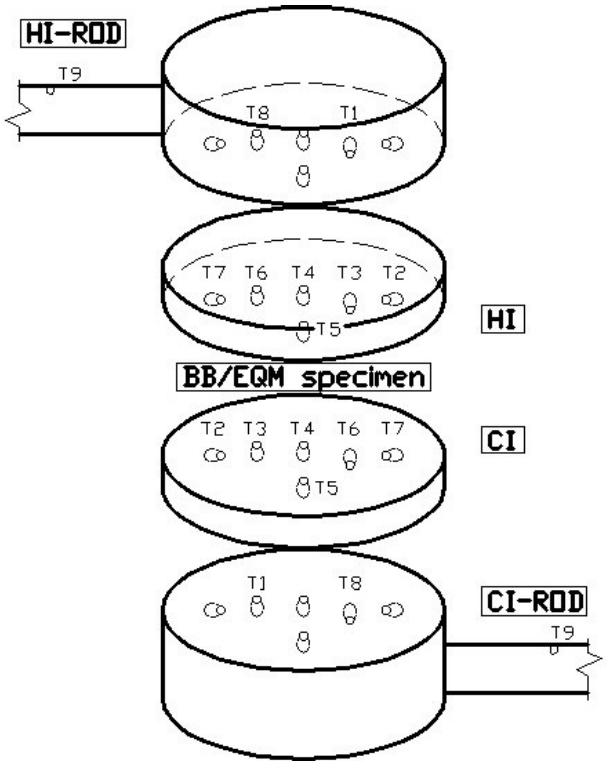

Figure 3.5: *Temperature probes layout within the inner HST Chamber assembly. [4]*

Pressure control system

The pressure control system has been upgraded significantly since Version 2 design. A brand new Turbo Pumping Station has been installed. The Station integrates two vacuum pumps and its control unit, a so called TIC Turbo & Instrument Controller (TIC). A newly installed Wide Range Gauge (WRG) replaced the original Pirani gauge, expanding the measureable pressure to high vacuum parameters. Communication and data exchange is now separated into two paths. The WRG is connected with TIC unit through Ethernet cable allowing measured parameter

– voltage to be evaluated (by TIC) in order to extract actual pressure value which is displayed on TIC main screen. Second data exchange path is in between TIC and ESAM, which transfers measured data to PC. ESAM desktop software records measured voltage value, value, indicating inner chamber pressure. The voltage-pressure convert formula depends on TIC menu settings of "Gas type". Hermetical isolation of the HST Chamber can be achieved by closing newly added Ball Valve 2, installed on the top of the vacuum pump. On the other hand, outgassing of the chamber can be done by opening Ball Valve 1, mounted on the top flange. ***Note:*** *Use Ball Valve 1 (placed on the top flange) for equalizing test device inner pressure with the ambient one. The Ball Valve 2 should be always opened once there is an atmospheric pressure inside of the HST Chamber. Sudden pressure changes could cause damaging of the Turbomolecular pump when opening Ball Valve 2 in uneven pressure state.*

Pressure control system:

- Turbo Pumping Station (Part No.: TSK1E1001) [6]
  - Vacuum pumps (Backing pump: nXDS10i; Turbomolecular pump: nEXT85H NW40)
  - TIC Turbo & Instument Controller (200W; D397-22-000) [7]
- Wide Range Gauge (WGR-S-NW25 200; D147-01-000) [8]
- Ball Valve 1 (IBV16MKS; C360-00-100)
- Ball Valve 2 (IBV40MKS; C360-00-300) [9]

Vacuum pumps: a newly installed vacuum system is capable of creating intended Qualification environment of 1·10-5 mbar. The turbo Pumping Station combines two separated pumps in order to cover wide range of pressures. Vacuum pumps are:

- Turbomolecular pump (nEST85H)
- Backing pump (nXDS10i)

Vacuum pump system monitoring, function and settings are done through a TIC unit. System links, sequences and turbo pump mode can be set as well. Turbomolecular pump is expanding the minimum possibly reachable pressure.

TIC Turbo & Instrument Controller: is a compact control unit, delivered as a part of the Turbo Pumping Station assembly. Both Turbomolecular and Backing pump state, gauge connection and gauge pressure indication can be observed on the main display. Further vacuum pump´s setting can be done through the TIC menu as well. The turbomolecular pump, Backing pump, and WRG represents the inputs, while the only output – logical interface is connected with ESAM. The TIC main menu can be seen in Figure 3.6.

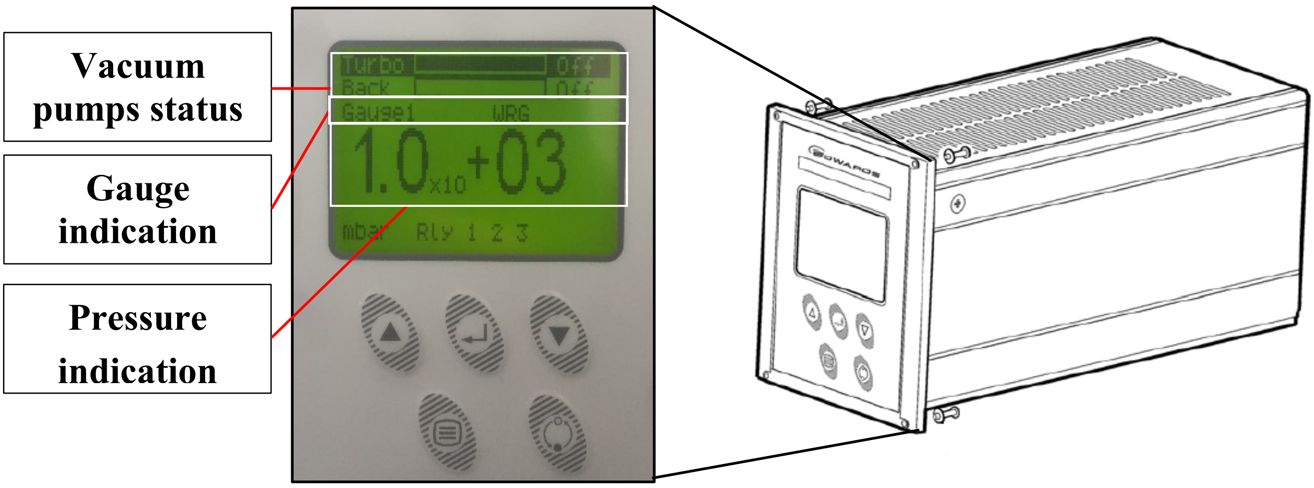

Figure 3.6: *TIC unit & TIC Main screen*

Wide Range Gauge: combines inverted magnetron and Pirani gauge in a single compact unit securing wide-range pressure measurements. The WRG is gas dependent, meaning the gas type has to be selected on TIC prior to all measurements. The gauge is mounted vertically to the top flange of the chamber in accordance to supplier´s recommendation. Output is FCC68 connector socket, further connected to TIC. The output signal is voltage, which needs to be converted according to the V-P equation (1) stated below. However, the TIC unit recognizes connected gauge and converts voltage to pressure automatically. TIC Gauge menu is shown in Figure 3.7. Equation knowledge is important for post data evaluation. The WRG dimensions can be observed in Figure 3.8.

$$p = 10^{(1.5 \cdot V - 12)}\ [mbar] \tag{1}$$

Figure 3.8: *TIC Gauge settings. The HST Chamber inner gas type is selected here. Automatic calibration can be sent by entering the "calibration" option.*

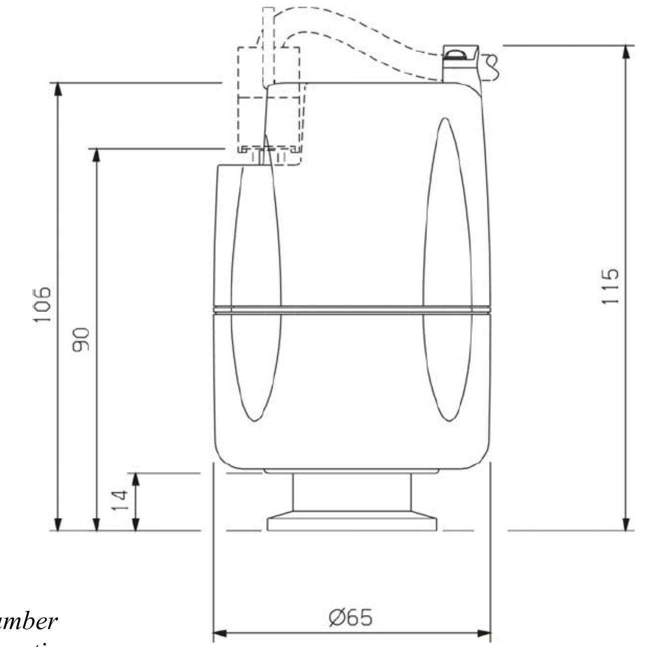

Figure 3.7: *WGR-S-NW25 200 dimensions.*

Note: *WRG position was changed during initial CO_2 cycle tests in order to determine the TIC pressure indication accuracy. Since CO_2 is heavier than air, the majority of the gas possibly descends to the bottom of the HST Chamber. Therefore, low horizontal position was found to be better.*

Procedures of creating of low pressure environment inside of the test facility can be slightly different for CO_2 and air tests as a medium. CO_2 vacuum creation procedure is described in CO_2 supply system subchapter.

HST Chamber high air vacuum creation procedure:

A. Turn on the vacuum pump power supply (TIC back side)
B. WRG ignition – track 10 minutes (minimum)
C. Check the HST Chamber tightness
D. Hermetically close HST Chamber (except "*Ball Valve 2*" which connects pump with the chamber)
E. Set *Gas Ballast* control to "ON" (Position "1")
F. Set *Gas Type* to N_2 (TIC – gauge settings)
G. Consider *Calibration command* option (TIC – gauge settings)

H. Check the pressure indication on the TIC Main screen
I. *Cycle ON* the system (Main screen, min. 10 minutes after WRG ignition, if the indicated pressure corresponds with atmospheric pressure)
J. Set a *Gas Ballast* control to "OFF" (Position "0", min. 20 minutes after the System was *Cycled ON*)
K. Eventuality:
   - Close the *Ball Valve 2* & turn off Vacuum pump (Hermetical isolation of HST Chamber, pressure would rise during the time)
   - Let the system be open with Vacuum pump working
L. Cycle system "OFF"

CO_2 supply system

The CO_2 supply system is used for simulating Martian atmosphere during BB and EQM tests (50/100 Pa of CO_2). It´s main parts are:

- CO_2 tank (8.2 dm^3; 2x107 Pa – 200 bar)
- Reduction valve (300 bar / max. 2 bar)
- Leak valve (LV10K Fine Control Leak Valve)´
- Ball Valve 1 (IBV16MKS; C360-00-100)
- Ball Valve 2 (IBV40MKS; C360-00-300) [9]

Storage of CO_2 gas is a conventional CO_2 overpressure tank, meaning that the pressure has to be reduced before feeding the chamber. It is done by a Reduction valve by decreasing the pressure from 200 bar to 0 ÷ 2 bar output since the maximum input to the Leak valve is 2 bar. WRG measurement is inaccurate at atmospheric pressure range. Therefore, setting the Reduction valve to about 0.5 bar (0.5 atmosphere) should secure the maximal HST Chamber overpressure of 0.5 bar, even if the TIC pressure indication is stuck at $1 \cdot 10^3$ mbar (max. possible pressure displayed on TIC). Feeding CO_2 inside of the chamber is a complex task − the final inner state requires non-convection environment.

HST Chamber high CO_2 vacuum creation procedure:

A. Turn on the vacuum pump power supply (TIC back side)
B. WRG ignition – track 10 minutes (minimum)
C. Check the HST Chamber tightness
D. Hermetically close HST Chamber (except "*Ball Valve 2*" which connects pump with the chamber)
E. Set *Gas Ballast* control to "ON" (Position "1")
F. Set *Gas Type* to CO_2 (TIC – gauge settings)
G. Consider *Calibration command* option (TIC – gauge settings)
H. Check the pressure indication on TIC Main screen
I. Cycle on the system (Main screen, min. 10 minutes after WRG ignition, if the indicated pressure is corresponding with atmospheric pressure)
J. Pre-set Reduction valve to 300/0.5 mbar
K. Set a *Gas Ballast* control to "OFF" (Position "0", min. 20 minutes after the System was *Cycled ON*)
L. Perform CO_2 Cycle (at least 3 times):
   - Close the *Ball Valve 2*
   - *Cycle OFF* the System
   - Check the *Reduction Valve* settings (ideal 200/0.5 mbar)

- Fully open the *Leak Valve* (HST Chamber shall be overpressured to 0.5 mbar)
- Close the *Leak Valve* (if no additional CO_2 inlet feeding detected)
- Open *Ball Valve 1* (***Note:** the tube outlet must be placed outside!*)
- Close *Ball Valve 1* (If no CO_2 is leaking out, HST Chamber shall be at atmospheric pressure)
- Open *Ball Valve 2*
- *Cycle ON* the System

M. Close *Ball Valve 2* & *Cycle OFF* the System (Hermetical isolation of HST Chamber, CO_2 pressure would rise during the time)

HST Chamber Mars atmosphere creation procedure:

A. Repeat "*HST Chamber high CO_2 vacuum creation procedure*" steps A to L
B. Perform at least three CO_2 Cycles (step L, then continue with actual step M)
C. Close the Ball Valve 2
D. Cycle OFF the System
E. Check the Reduction Valve settings (ideal 200/0.5 mbar)
F. Open & Control the Leak Valve outlet (check inner pressure indication)
G. Close the Leak Valve once intended pressure is indicating on TIC Main screen

Data acquisition system

ESAM Traveller was chosen as a DAS unit to collect the measured data. 32 data channels allow to cover all types of measured input signals and transfer them continuously real-time with 8 MB / sec via USB port to PC. Collected data are then displayed and can be further processed and evaluated trough connected PC.

- ESAM Traveller 1CF (32 Channels; version 2.5)
- PC

ESAM PC software needs to be turned on when the measurement starts. The collected data consist of: temperature progression recording (in dependence in the used measuring probes), pressure progression recording.

HST Chamber Version 3 layout

The test facility was relocated to the newly reserved cleanroom on IAE. The actual HST Chamber Version 3 layout can be observed in Figure 3.9. The workplace section can be seen in Appendix A5.

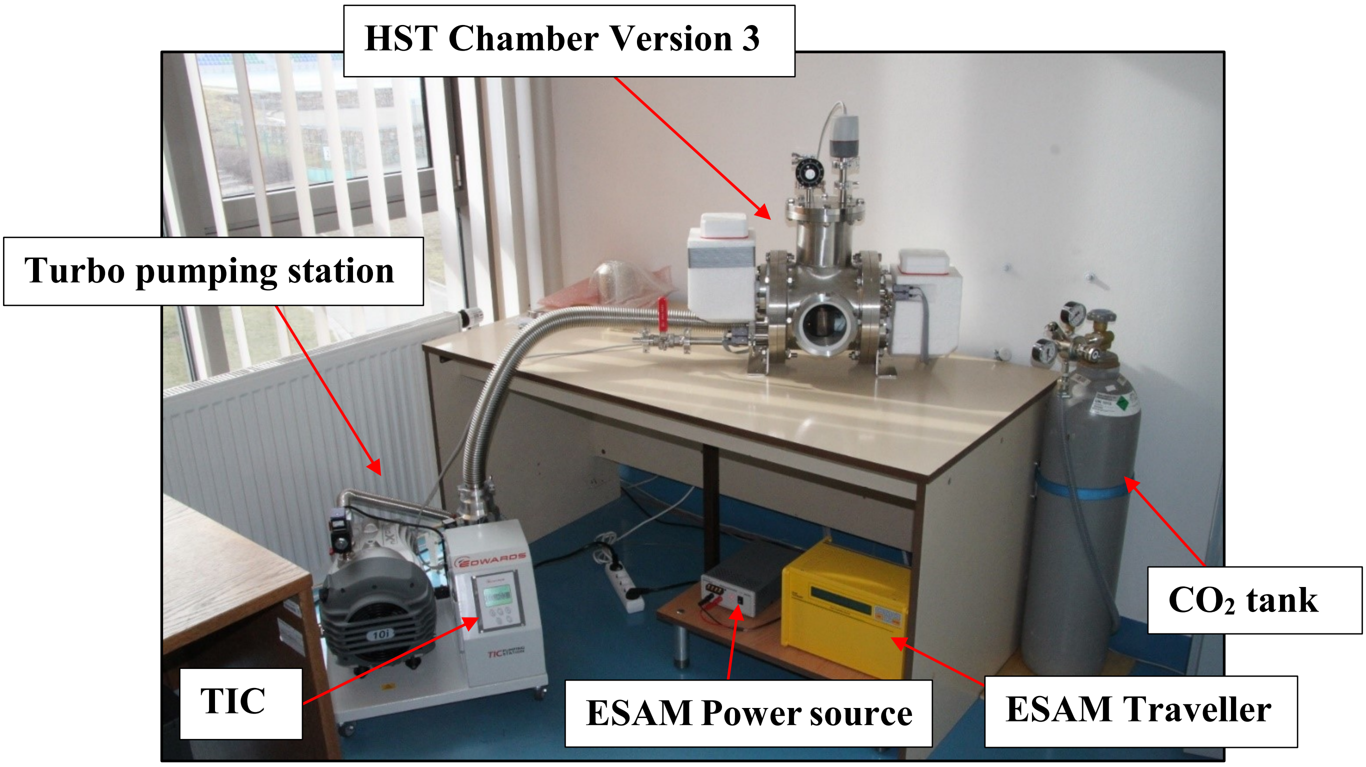

Figure 3.9: *HST Chamber system layout.*

3.5 Upgrades breakdown

The following list presents all the HST Chamber version 3 upgrades in comparison with the previously used HST Chamber version 2 – Advanced. The HST Chamber Version 3 system scheme can be observed in Figure 3.10.

Test chamber construction:

CI flange modification	4 vacuum feed-throughs total. 16 thermocouples installed

Temperature control system:

New HI Power source	DPS-3005D 30V/5A, allows fine output power tuning in constant current/voltage regime

Pressure control system:

Ball Valve 2	allows hermetical isolation of the HST Chamber
Vacuum pump station	capable of creating $1\cdot10^{-5}$ mbar environment, TIC – automatic gauge calibration
WRG	precise low-pressure gauge, automatic gas-dependent output

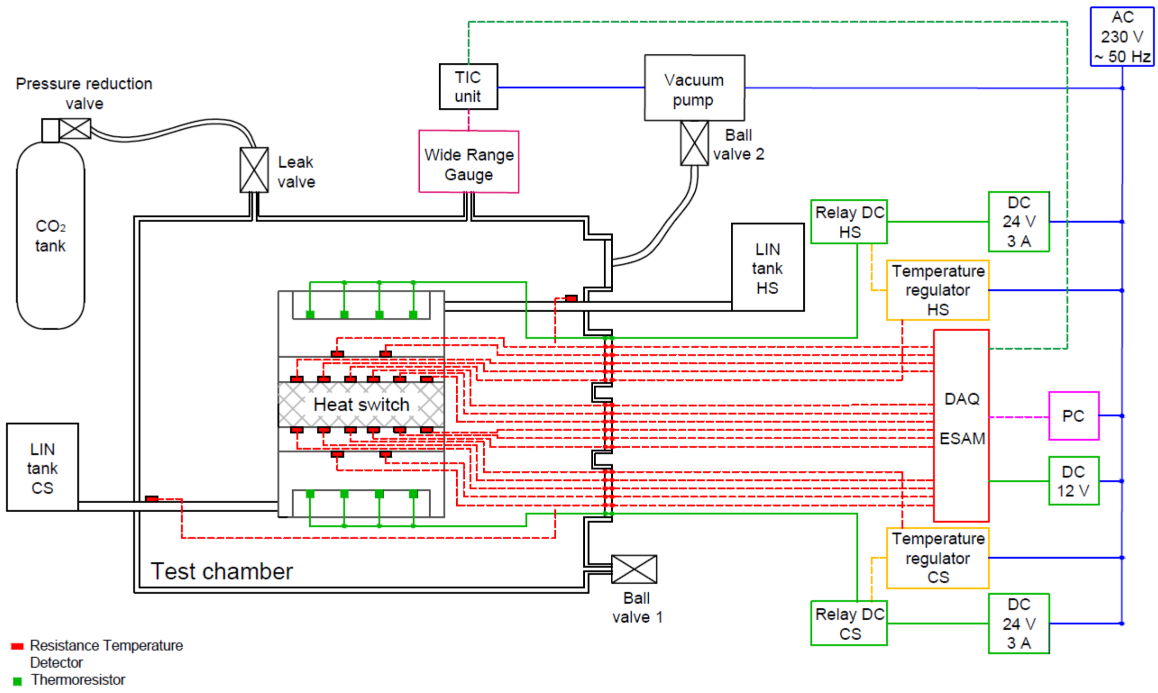

Figure 3.10: *HST Chamber Version 3 upgraded system scheme.*

4 HST CHAMBER MEASUREMENTS

The HST Chamber was designed in order to evaluate the BB/EQM specimen conductance. However, the conductance has to be determined based on the measured & input parameters knowledge. A steady state of the measurement assembly must be recorded to be able to extract the evaluation inputs.

4.1 Measurement assembly

The measurement assembly is composed of the inner HST Chamber parts:

- Hot Interface
- Hot Copper plate (upper)
- Specimen
- Cold Copper plate (lower)
- Cold Interface

The temperature probes are glued in the specific assembly layer grooves. The probes position and tagging is crucial for the evaluation process. The probes layout within the measurement assembly could be seen in the chapter 3.4.4 Test Chamber V3 systems, Figure 3.5.

4.2 Input parameters

The test conditions are achieved by the specific HST Chamber subsystem settings. Particular test inputs may differ within the actual test design. However, the specimen measurements are performed with these input parameters:

HI thermal load: a prescribed input power is applied on the HI. The heat applied is determined based on the actual HI Power source output current I [A] and HI resistors resistance.

$$Q_{in1} = R_{HI} \cdot I_{out}^2 \ [W] \quad (2)$$

Current values should be set on the DPS-3005D by the voltage U [V] adjustments in order to obtain some of the common test inputs:

Table 4.1: *HI Power source settings.*

Intended Q_{in1}	Power source I_{out}
[W]	[A]
2	0.5
4	0.707
7	0.935
10	1.118

A constant input power is secured by the HI Temperature Controller setting. The set temperature must be high enough, so the relays do not interrupt the HI power load.

CI temperature: a constant TC2-7 temperature should be maintained during the measurement. The reference temperature is set on the CI Temperature controller, which is powered by CI Power source. Maintaining a constant temperature value requires a CI cooling, done by a manual LIN application to the CI LIN storage.

4.3 Measured parameters

The inner HST Chamber parameters are recorded by the ESAM during the test. A set of the ESAM output values is presented below:

Temperatures:*	
HI	TH 1, 8
Copper plate (hot)	TH 2, 3, 4, 6, 7
Copper plate (cold)	TC 2, 3, 4, 6, 7
CI	TC 1, 8
CI rod	TC 9
Inner chamber temperature	TH 9
Pressure	TIC (WRG)

* Temperature probes TH5 & TC5 are the reference inputs for the HI & CI Temperature controllers. Therefore, the values are not recorded by the ESAM.

4.4 Measurement execution

Test procedures: a newly defined Test procedures should be followed in order to perform the HST Chamber version 3 measurements. The actual Test procedures are covered in *8.1.2 Test procedure.*

Steady state definition: the steady state is detected once a constant temperature difference within the measurement assembly is achieved. While the TC2-7 temperature is being maintained constant, a constant temperature should be eventually established on the hot Copper plate during the measurement as well. The final TH2-7 temperature depends on the specimen, layers and layers contact thermal resistances.

The measurement should be terminated once a steady state of the measurement assembly is recorded for at least 25 minutes. However, it is possible the steady state would not be reached due maximal assembly temperature limitation + 60 °C derived from the glue specifications. Low thermal conductivity specimens causes the unallowable TH2-7 & TH1,8 temperature growth.

4.5 Test evaluation

The final specimen conductance is calculated based on the measured thermal difference and assumed thermal load.

Temperature differences: the measurement results are processed in the pre-prepared evaluation matrix. Average HI, Copper plates and CI temperatures are determined for the further temperatures differences definition:

$$
\begin{aligned}
\Delta T1 &= TH1,8 - TH2\text{-}7 \\
\Delta T2 &= TH2\text{-}7 - TC2\text{-}7 \\
\Delta T3 &= TC2\text{-}7 - TC1,8
\end{aligned}
\tag{3}
$$

Thermal load: Q_1 [W] input power is applied to the HI. However, the actual specimen input/output heat must be appointed in order to calculate the conductance. The heat determination process depends on the evaluation method used.

The original HST Chamber V2 evaluation method presented by Ing. Jakub Mašek in his Master thesis *Qualification test of heat switch for Martian conditions* [4] is based on the cumulative heat losses coefficient application.

A new HST Chamber version 3 evaluation approach is presented in chapter *7 Mathematical model of the heat transfer in chamber*.

The specimen conductance C [W/K] is calculated from the measured ΔT2 and associated heat value.

HST Chamber V2 original evaluation method:

$$C_{cal2} = \frac{Q_2}{\Delta T2}\ [W/K] \tag{4}$$

HST Chamber V3 Thermal Model evaluation method:

$$C_{SPCM} = \frac{Q_{out3}}{\Delta T2}\ [W/K] \tag{5}$$

The schematic Figure 4.1 define the evaluation parameters within the measurement assembly.

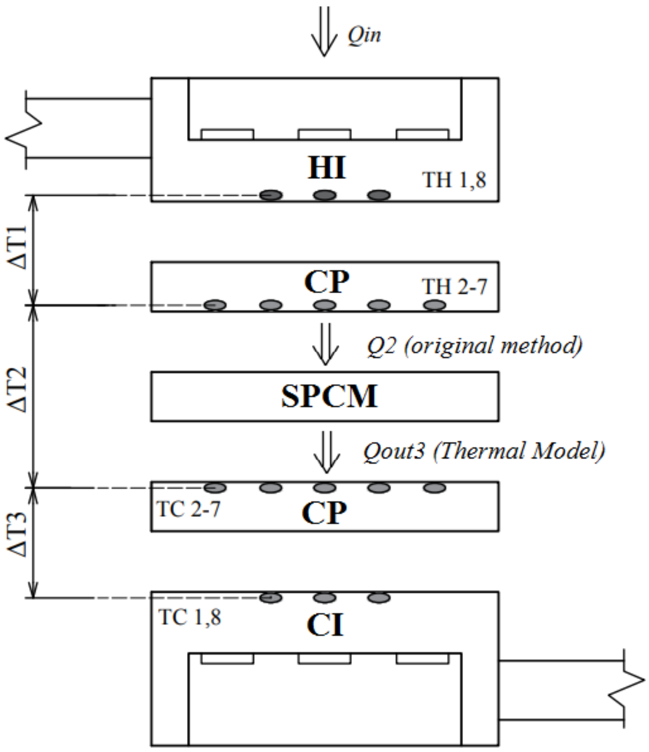

Figure 4.1: *The measurement parameters schematic definition.*

4.6 Test design

ESA together with Aero Sekur defined the test campaign consisting of two BB and three EQM test cycles. However, the proposal was processed into the actual modified test campaign consisting of BB and EQM test blocks.

Two tests blocks designs are the same for BB and EQM tests and should determine the conductance transition range. The third test block prescribed for EQM testing simulates extreme temperatures during a Martian diurnal cycle (Sol). [4]

HST Chamber version 3 measurement settings should mimic one of the Block test designs.

4.6.1 Block I

Constant temperature on the CI is maintained, while changing the power input on the HI by steps from 1 to 10 W. The experiment should detect the BB/EQM transition range width. Cycles are to be performed at least three times to confirm the transition repeatability. Every heat load should be applied for at least 2 hours, after 30 minutes temperature stabilization. The block test design can be seen Figure 4.2.

Input parameters: HI thermal load (1-10 W)

CI temperature (-15, 0, 15, 30 °C)

Output parameters: HI temperature

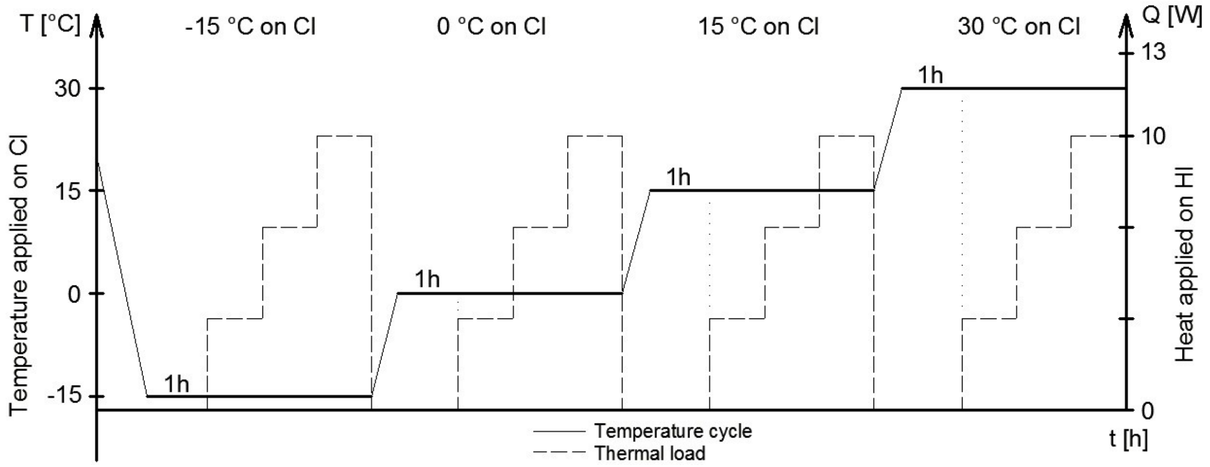

Figure 4.2: *Block I test cycles. [4]*

4.6.2 Block II

Constant power of 10 W is maintained on the HI, CI temperature is changing in a range:

- BB: -15 °C to +30 °C
- EQM: -60 °C to +50 °C

At least 3 cycles are required. The cycles should last for a minimum of 6 hours for BB and 12 hours for EQM tests with 1 hour held at each temperature.

MHS conductivity C [W/K] calculation with CI temperature variation in the predicted conductivity transition range and HI maximum heat load of 10 W. The specimen conductivity change should be observable in the conductivity-HI temperature charts.

Input parameters: HI thermal load (10W)

CI temperature (depends on the specimen type)

Output parameters: HI temperature

Both BB and EQM Block II test cycles can be further observed in the Figures 4.3 & 4.4.

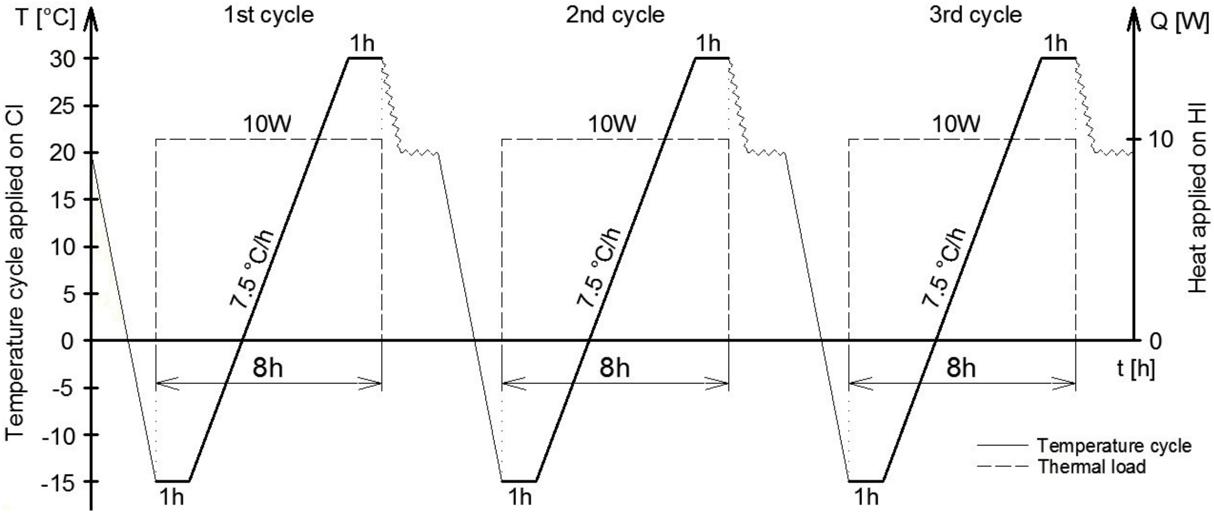

Figure 4.3: *BB Test Block II. [4]*

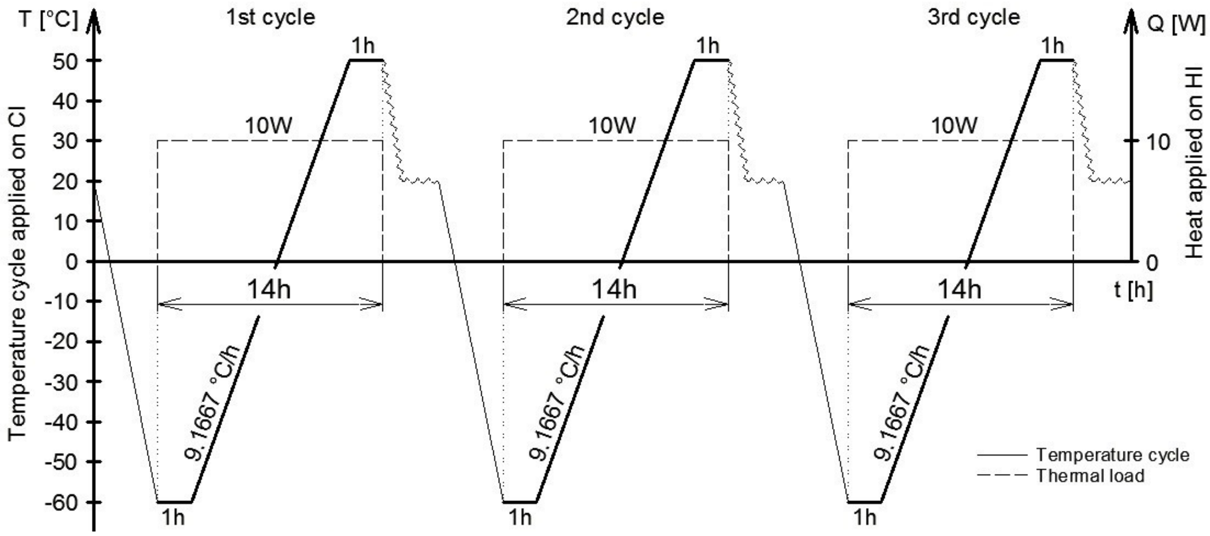

Figure 4.4: *EQM Test Block II. [4]*

4.6.3 Block III (EQM Qualification test)

The temperature cycles are applied on both Hot and Cold Interfaces, although with different temperature ranges. The temperatures change simultaneously during 24-hour lasting cycle. The temperature extreme shall be kept for at least 1 hour.

The test aims to confirm the MHS functionality during different temperature cycles applied on both HI & CI. The cycles simulate a real dial environment on Mars. Transition range of the Specimen should be confirmed and established as well. The results are to be presented in charts.

Input parameters: HI temperature evolve during cycle

CI temperature evolve during cycle

Output parameters: HI heat flow during cycle

CI heat flow during cycle

Hot & Cold Interface temperature within 24 hour cycles can be observed on the Figure 4.5 below.

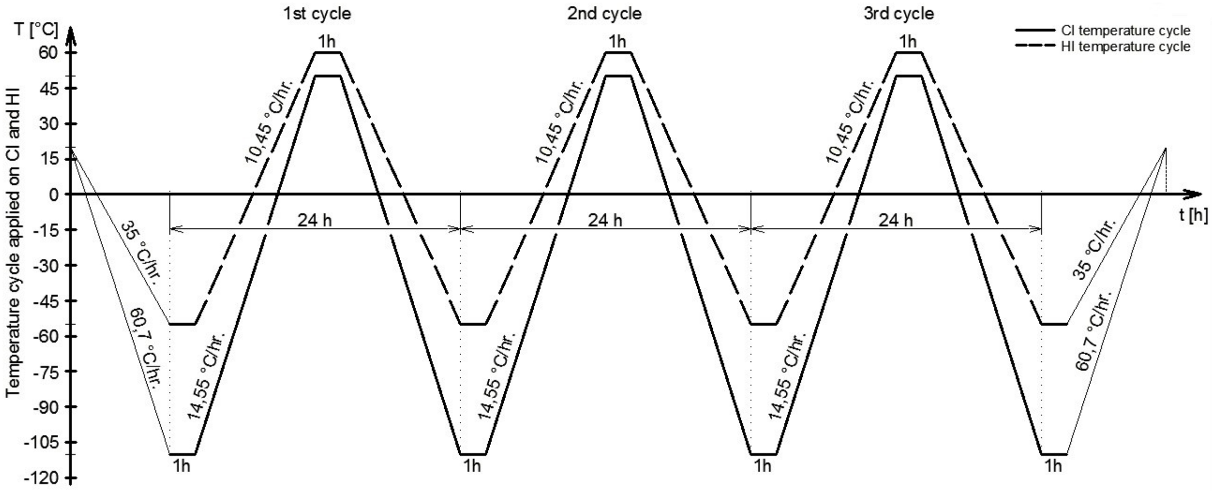

Figure 4.5: *EQM Test Block III. [4]*

5 CALIBRATION PROCESS DEFINITION

This chapter covers the HST Chamber Version 3 calibration plan proposal. Designed calibration process was divided into several phases including HST Chamber Version 3 system tests, specimen definition & production, specimen measurements and mathematical model evaluation. The calibration outcome should define the test facility capability, performance limits and evaluation process correctness & accuracy.

5.1 HST Chamber version 3 calibration phases

The proposed calibration plan relies on comparison of the calibration specimen measurements results and the Thermal Model v1.1 simulation. The final HST Chamber Version 3 calibration coefficients will be determined once the simulation & measured outputs are the same. However, the measurement unknown variables have to be extracted from the initial Thermal Model v1.0 results.

5.1.1 HST Chamber System performance experiments

System composition of the modified Version 3 HST chamber was finished during the February 2019. Upcoming facility system tests had to prove its successful installation, integration and limits. The facility system tests included pressure, thermal and environmental tests, as it was mentioned in *2.5.2 Calibration test phase*. The cleaning & assembly process as well as the established workplace configuration are documented in the Appendix A5.

Pressure tests: mostly included vacuum pump experiments. Its initial setting and device understanding was crucial for the future Test procedures definition. Information about the minimum pumping time required and pressure influence aspects was also gathered. The system experiments composed of:

- Minimal Pressure Test (Measurement 20001, executed 18.3.2019)
- Foam Influence Test (Measurement 20004, executed 22.3.2019)

Thermal tests: aimed at exploring the temperature control system full functionality and interface heating pressure influence.

- Heating Influence test (Measurement 20006, executed 5.4.2019)

Environmental tests: CO_2 atmosphere cycle test was performed in order to confirm the HST Chamber V3 subsystem functionality.

- CO_2 Atmosphere Test (Measurement 20007, executed on 10 April 2019)

5.1.2 Calibration specimen design

Calibration experiments should be performed with standardized dummy specimens, reducing the uncertainty level by replacing unknown MHS properties with predefined dummy characteristics. Specimen requirements were put together based on previous 2nd-generation dummies measurements experience. The final V3 Dummy design is described in the chapter *4 Calibration specimen.*

5.1.3 Mathematical model simulation

The complex mathematical model coded in the MS Excel software was designed to describe & evaluate heat processes in the measurement assembly of the HST Chamber version 3. First version of the Thermal Model is prepared for Block I experiments evaluation. The Thermal Model v1.0 results should serve for the future model refining. Enhanced Thermal Model v1.1

should be able to simulate the specimen measurements results. The Thermal Model is presented in chapter *7 Mathematical model of the heat transfer in chamber*.

5.1.4 Calibration specimen experiments

Calibration specimen measurement will test the Thermal Model v1.0 evaluation functionality HST Chamber version 3 capability. The experiments should also acknowledge defined Test procedures provide the results for the Thermal Model refining. The measurement execution & evaluation is described in chapter *8 Calibration specimens measurement.*

5.1.5 Final calibration coefficients

The final calibration coefficients will be derived from the Thermal Model v1.1 and calibration specimen measurement comparison, once the results are consistent. A set of coefficients should be prepared for the upcoming Qualification test Blocks.

6 CALIBRATION SPECIMEN

As it was mentioned before, the calibration task relies on measurements of standardized specimens specially prepared for this purpose. A new generation of specimens should replace previously used Dummies I and II. Both original Dummies generations were used for chamber V1, V2 and V2 advanced. experiments and measurements. Since the design of the test facility brings a new possibility in terms of expanded simulated conditions, third generation Dummies are demanded to explore extreme cases of measurement.

6.1 Specimen requirements

Specimen Dummy V3 (Version 3, latest generation of the specimens) was designed with respect to its further purpose. Before defining the final specimen properties and parameters, initial performance requirements were formulated. Requirements could be classified in two major categories:

- Physical properties of the Dummy V3
- Performance properties of the Dummy V3

Both of these categories were equally mandatory since the chamber design and dummy task practically reduce possible design options.

Dummy V3 physical properties requirements

Physical properties requirements include three main conditions, originally formulated and further demanded in order to design a substitutable specimen with a known parameters:

- Contact surface
- Simple heat transmission
- Height

The main condition that strongly reflects design possibilities of the Dummy V3 is contact surface of the specimen. To minimalize heat leakages from the Hot and Cold Interface, it would be convenient to cover most of the interface surface with a Dummy V3 contact. On the other hand, to stick with original MHS construction, the contact surface should be roughly about 16 cm^2. Final Dummy V3 properties are presented at the end of the chapter.

Simple heat transmission through the specimen is one of the associated physical properties demand. The idea is that the specimen shall be able to transfer most of the heat applied to the hot side. While the contact surface area is minimalizing the heat leakages, the contact-less parts of the Dummy V3 shall be simple to allow heat transmission just in one way. Heat applied to HI further proceed through V3 Dummy – from the hot (top) part, trough contact-less mid part to the cold (bottom) CI contact part. Three approaches were considered to finally come up with final solution. Development approaches included: tube as a one part specimen, cross oriented plates as a one part specimen and combined three parts specimen. The tube specimen design was abandoned due to its small contact surface which did not reflected the original MHS design. The cross specimen was abandoned due to the same reason, moreover the radiation area would be bigger than MHS one as well.

Height of the specimen was considered as well. The inner HST chamber layout allows reduced possibilities in terms of specimen position and assembly. Although the height was adapted to secure performance properties of the Dummy, the latest drafts calculate with MHS like height. For this case, the height limit was locked on 26.2 mm.

Dummy V3 performance properties requirements

Performance properties requirements are directly connected with a dummy purpose. The dummies experiments should represent further MHS measurements, therefore its performance should also mimic the MHS functionality. What is more, V3 Dummies experimental testing should also verify the applied measurement method and data evaluation, and provide clear results about the HST chamber behavior. The main performance demands are defined as:

- Thermal conductivity
- Simple heat transmission
- Thermal contact resistance

V3 Dummies with exactly known thermal conductivity are the primary tool for HST chamber calibration. To evaluate the inner chamber environment influence and measurement accuracy during the experimental testing, manufactured specimens must perform according to the initial calculations. Third generation Dummies simulate 3 states of MHS in terms of thermal conductivity. While MHS thermal conductivity depends on the temperature on one of the sides, specimens should simplify this behavior. This resulted in three V3 Dummies designed, each with one specified thermal conductivity which simulates one of the MHS states.

- V3 Dummy Closed; thermal conductivity k = 1 [W/K]; representing close ("ON") position
- V3 Dummy Open; thermal conductivity k = 0.01 [W/K]; representing open ("OFF") position
- V3 Dummy Mean; thermal conductivity k = 0.2 [W/K] is additional specimen, which will test measurement and evaluation accuracy rather than simulating temporary MHS state.

The switch ratio between the open and closed state should be the highest possible (max. 100%). While the other design requirements reduce the possibility of getting the exact thermal conductivity level, the final switch ratio is also slightly different. V3 Dummy Mean thermal properties requirements are based on the previous HST Version 2 & BB experiments.

The requirement of simple heat transmission resonated even in performance demands. As it was mentioned earlier, MHS varies its thermal conductivity based on the temperature applied to one of the sides. On the other hand, V3 Dummy design should secure constant performance during the experiments, in variable conditions.

Thermal contact resistance falls into two areas. Thermal contact resistance between HI/CI & V3 Dummy and V3 Dummy part design. In general, thermal contact resistance should be as low as possible in order to precisely determine the input parameters of the measurements. Since the thermal contact resistance should be as low as possible even at the Dummy design level, one-part construction was required. Any multi-part assembly solution could cause unpredictable heat transfer paths due to imperfect surface contact. V3 Dummies are designed as standardized specimens with pre-calculated precise properties.

6.2 V3 Dummies design review

With respect to all requirements mentioned in the subchapter *6.1 Specimen requirements*, three III. generation calibration specimens were designed in CATIA software and further manufacture. CATIA models can be used for other thermal simulations, e.g. in ANSYS or a general HST Chamber assembly visualization. Complete V3 Dummies design reviews are presented in this subchapter, while the final production drawings are attached in Appendix A2. Dummy V3 Closed & Mean construction is very similar. On the other hand, V3 Open approach was slightly different, resulting in its separated description.

6.2.1 Dummy V3 Closed & Mean

After initial requirements establishment, it was obvious that the best suiting design approach for closed (k = 1 W/K) and mean (k = 0.2 W/K) specimens would be based on the Dummy II construction. The comparison between the actual MHS, 2[nd] generation dummy and 3[rd] generation dummy can be observed in the Figure 6.1.

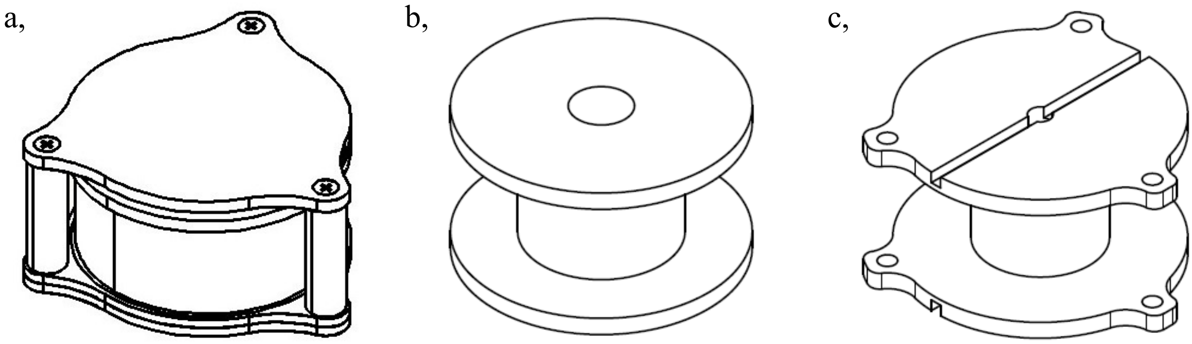

Figure 6.1: *BB (a), Dummy II (b) and V3 Dummy Closed (c) specimens comparison.*

Material: in order to minimalize the risk of material corrosion, Cu alloys were chosen as a suitable and affordable material. Also material thermal conductivity would be considered. Bronze CuSn8 has been chosen for its thermal conductivity λ = 62 W/m/K, which allows easy V3 Dummy modifications. While the main design remain the same, changing thickness of the material in middle section would influence final design properties. (Material used for Dummy II was Stainless Steel/Cu)

Construction: one-part body specimens were required to secure minimal thermal contact resistance and unwanted heat transmission paths. Although V3 Dummies Closed and Mean are in accordance with mentioned demand, their construction can be divided into three sections. Top and bottom sections are round disks, with diameter D = 45.7 mm and surface S = 15.5 cm^2. Each disk is completed with three connection pads, which allows the V3 Dummy to be screwed together with copper plates. Screwing the specimen with the copper plates improve quality of the surface contact. Outer pads diameter corresponds with the copper plate geometry. 2 mm thick, 2 mm high continuous groove connects the central hole. The hole diameter is 4 mm in both Closed & Mean design. The groove and the pads are the most noticeable modification in contrast with Dummy II solution. Grooves should secure proper inner vacuuming of the specimen. The disks are 3 mm thick. The disk construction along with connection pads, vacuum groove and central hole can be observed in Figure 6.2. The CATIA models comparison can be found in the Appendix A3.

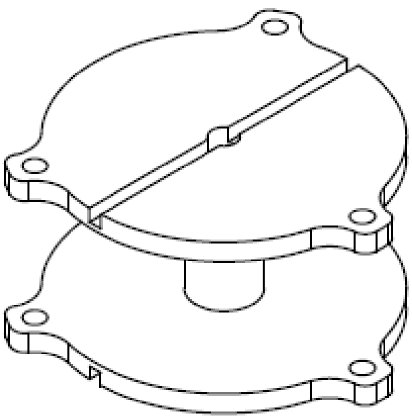

Figure 6.2: *V3 Dummy Mean.*

A tube with its inner diameter of 2 mm creates the middle section, which is 20.2 mm height and connects both top and bottom disks. Outer middle section diameter was adjusted according V3 Closed and V3 Mean requirements. In case of V3 Dummy Closed, the outer diameter of the middle section is 21.5 mm, while in case of V3 Dummy Mean just 10 mm. The overall specimen´s height

26.2 mm complies with MHS geometry. The V3 Closed & Mean dimensions can be observed in Figure 6.3.

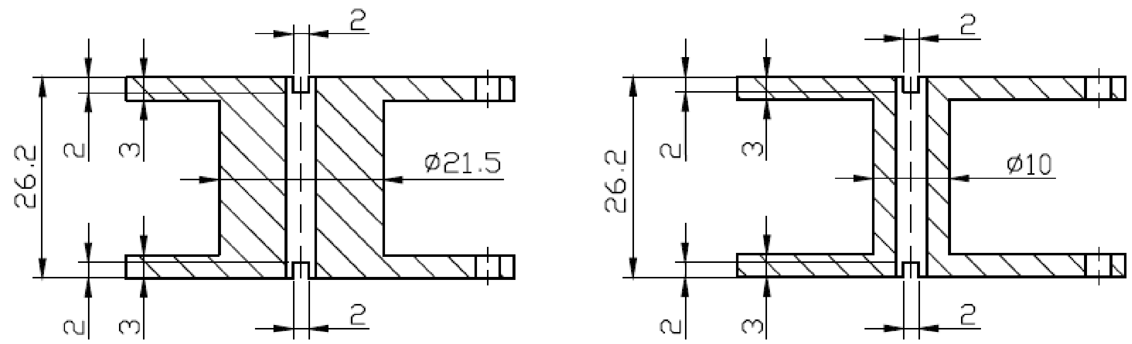

Figure 6.3: *V3 Dummies Closed (a) and Mean (b) comparison. Different middle section diameters allows to adjust the final specimen conductivity.*

Properties: final calculation of the thermal conductivity was divided into three parts according mentioned construction sections. The height, material and interface contact surface area would influence the final properties. Thermal resistance of all three section was calculated in both cases. Thermal conductivity than depends on resistance parallel/series combination. V3 Dummy Closed ´s calculated thermal conductivity is: k = 1.0079 W/K, V3 Dummy Mean´s calculated thermal conductivity is: k = 0.2000 W/K.

6.2.2 Dummy V3 Open

V3 Dummy Open demand of extremely low thermal conductivity (k = 0.01 W/K) required different approach than in V3 Closed & Mean solution. Previously designed generation II Open dummy labored with even thinner middle section (according Dummy II generation design) what turned out to be very unstable. Upgraded V3 Dummy than relays on single rod geometry.

Material: thermal insulation material PTFE was determined to be suitable for V3 Open construction. MHS in its open state transfers the applied heat just through Torlon columns, resulting in very low thermal conductivity. The PTFE and Torlon thermal properties are similar: λ = 0.26 W/m/K.

Construction: simple heat transmission, sufficient contact surface area as well as height demands were secured by simple rod construction. Thanks to low thermal conductivity of PTFE, MHS equivalent diameter D = 45.7 mm and height h = 26.2 mm were possible to be used. Also contact surface area of S = 16 cm^2 is maintained. V3 Open dummy is pad-less, since the screw connection would cause overheating of the pads due to thermal insulation properties of the material used. It is believed that the heat distribution would be uneven. V3 Dummy Open geometry section view can be observed in Figure 6.4.

Properties: the calculated V3 Open thermal conductivity is 0.016 W/K. Heat distribution shall be secured by a simple construction design. Surface contact area is satisfying and should gather most of the heat applied as well.

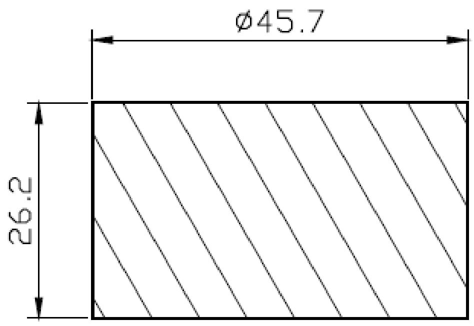

Figure 6.4: *V3 Dummy Open geometry.*

6.2.3 Dummies comparison

MHS, Dummy II (Closed, Open) and V3 Dummies (Closed, Open, Mean) conductance comparison can be observed in Table 6.1.

Table 6.1: *The MHS/Specimen conductance.*

Specimen	Closed [W/K]	Open [W/K]	Mean [W/K]	ON/OFF Ratio [%]
MHS	1	0.01	-	100
Dummy II	0.941	0.082	-	11
V3 Dummy	1.0079	0.016	0.2	63

Note*: the mentioned MHS conductance is based on ESA SOW Heat Switch Preliminary Specifications & requirements.*

7 MATHEMATICAL MODEL OF THE HEAT TRANSFER IN CHAMBER

To be able to effectively describe the inner HST Chamber phenomena during the test procedure, a coherent heat transfer Thermal Model was designed. Physically correct model should help to determine the unknown variables in order to evaluate the overall test device performance. The prime objective of the test facility is to measure MHS/Specimen´s thermal conductivity in various prescribed simulated conditions. Evaluation of Specimen measurement is done automatically after test results data import and actual scenario settings in Thermal Model. The unknown variables values are also included in the complex calculation, however have to be adjusted manually as a calibration parameters to be in conformance with the physical laws. Such a set input calibration parameters are stored and further refined once enough measurements are done. Coefficients derived from a multiple tests evaluation will be applied in advanced Thermal Model v.1.1 as a constants. With the unknown parameters reduced, actual Specimen measurement simulation & prediction would be possible.

Microsoft Excel has been chosen as a suitable tool for the heat transfer interpretation, originally designed for the HST Chamber Version 3 calibration task. The model of the heat transfer was originally designed for the HST Chamber Version 3 calibration & evaluation task. Supportive calculations run in separated program´s tabs, while the user´s interface is the main "*Thermal model*", which serves as an input & output window. A complex mathematical model should simulate heat losses & power drops during the experiment based on measurable and initially set parameters. Processes of the heat transfer through the assembly and low pressure influence are included in the software calculations. The final specimen conductance is derived from the steady state of measured parameters. Thus, the Mathematical model inputs shall be chosen in accordance with the steady conditions as well. An early version of the Thermal model is prepared for the Block I experiment conditions.

7.1 Test facility measurement assembly analysis

The Specimen measurement procedure remains the same as mention in chapter *4.4 Measurement execution*. The steady state data needs to be imported to the Thermal Model v1.0. However, the evaluation process is based on the newly defined Thermal Model v1.0 approach, which relies on heat losses calculation & assignment.

7.1.1 Heat losses determination

The possibility of exact specimen thermal conductance measurement is strongly decreased by heat losses through the assembly. Previous experiments showed that measured & calculated conductance of the specimen was roughly 60 times lower than the originally designed conductance. The error could be caused by: temperature probes inaccuracy, high heat & power leakages, evaluation process. While the temperature probes accuracy was confirmed by the test, this issue was excluded from the potential error list. The method used for conductance evaluation was also convincing enough to be excluded. Heat and power leakages than remain as the only fitting reason of the limited measurement possibility.

Low experiment pressure of 50/ $1 \cdot 10^{-5}$ mbar reduces the possibility of thermal exchange between the assembly and the inner chamber surroundings. Temperature of the measurement ambient gas $T_{amb.}$ [°C] must be measured to be able to determine the heat balance. Since the assembly can be hotter than ambient gas (CO_2/air), heat losses caused by thermal convection and radiation should be taken into account. On the other hand, the assembly receives the heat radiated from the HST chamber surface while it is cooler than the ambient gas. Power applied to the assembly is then changing thought the layers in dependence on actual layer temperature and thus thermal loses.

Temperature differences are caused by thermal resistance, especially by the Thermal Contact Resistance (TCR) between the layers. TCR is one of the unknown parameters which value was experimentally determined for purposes of this Master Thesis. It is believed the TCR value depends on: contact surface quality, roughness, flatness, materials in contact and potentially on heat applied. However, exact TCR description is a part of another research. TCR value determination is further presented in the subchapter *7.2.2 Thermal model calculation procedure.*

Assembly layers have thermal resistance as well. Opposite of the thermal conductance represents the resistance of the layer to conduct the heat. Thermal resistance can be treated as an electrical resistor in overall resistance determination. Measurement assembly conversion to the thermal resistance net diagram can be observed in Figure 7.1. The picture also shows radiation and convection thermal loses in the place of their application. The thermal model simulates heat & power leakages according to the mentioned scheme below.

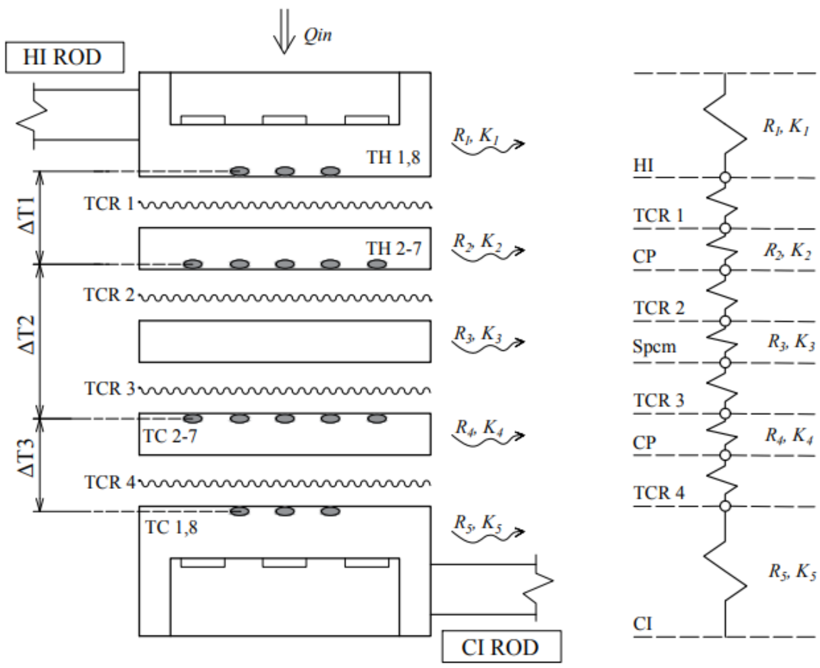

Figure 7.1: *The Thermal Model v1.0 parameters definition & resistance net construction.*

7.1.2 Assembly insulation

Thermal insulation of the assembly was designed in order to minimize expected as well as unexpected loses, which would affect the measurement in an unpredictable way. The Thermal protection design was inspired by commonly used MLI (multi-layer insulation) layers order. Renewed insulation solution can be observed in Appendix A5. Materials used are:

- PTFE tape
- Mylar foil
- Upilex foil
- Upilex foam

PTFE tape is very low conductivity insulation material which was applied on the CI & HI rods. Rods are affected by low temperatures due to their connection with the LIN tanks. PTFE layers should secure rod & ambient temperature constant difference so low temperature is applied to the CI & HI.

ESA provided the IAE BUT Brno with Upilex foam and foils. Foam was processed and shaped to surround the whole inner assembly. Three separated parts of the foam insulation were designed for the HI, Specimen and CI. Upilex foil was used as assembly closest thermal insulation layer. Upilex foam covered by Mylar foil is then used as a third insulation layer.

High reflective aluminized Mylar foils were glued the inner and outer sides of the Upilex foam parts. Low absorptivity Mylar should minimize the thermal radiation leakages. The film reflects the radiation of the HST chamber while the ambient temperature is higher than the assembly temperature, and reduces thermal losses from the hot assembly in cold assembly cases.

7.2 Thermal model simulation

The final HST Chamber thermal mathematical model combines the earlier mentioned phenomena. Measured & calculated specimen conductance should correspond with designed Specimen conductivity (depends on V3 Specimen type) once the Thermal Model v1.1 variables are set correctly. Results post processing should lead to the general test device calibration coefficients.

In accordance with MHS Validation test Blocks I, II & III (test Blocks description can be found in chapter *4.6 Test design*) complete mathematical simulation should include all the Block I, II & III input parameters.

The first version of the Thermal model is prepared for Block I measurement evaluation & calibration inputs generation. Calculation components are firstly evaluated based on suitable equations (modified by the input parameters) in the specific tabs. A complete Thermal Model breakdown is presented in functional diagram – Figure 7.2.

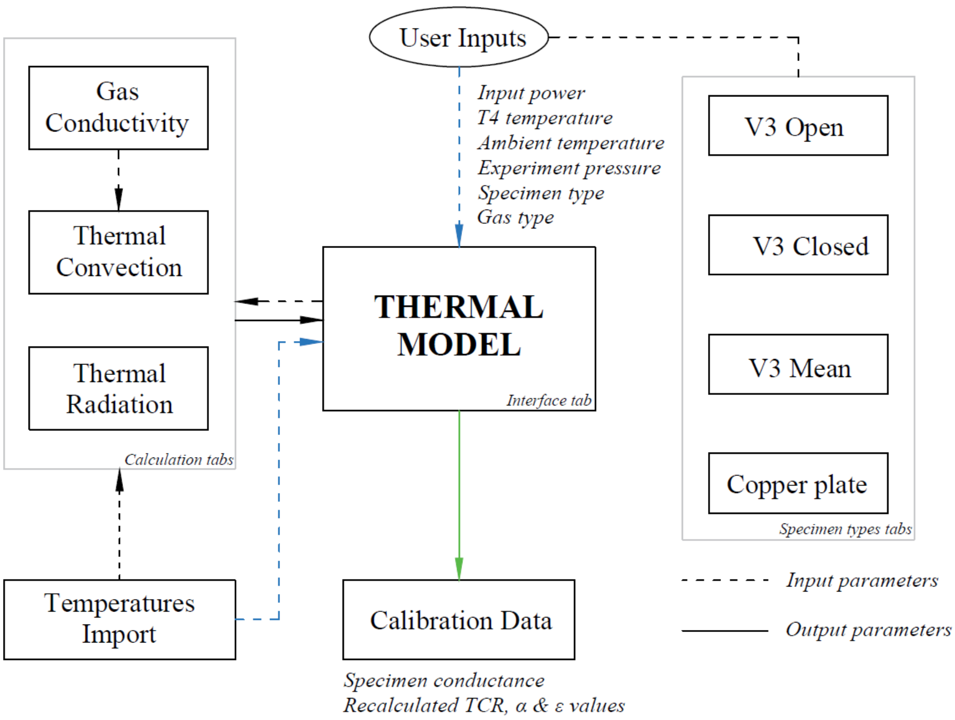

Figure 7.2: *The Thermal Model v1.0 software tabs with an input & output definition.*

Combination of Input temperature T4 & Input power allows to create a unique calculation index, characterizing the selected experiment conditions. The final calibration inputs and evaluation results are indicated in the user interface window in Thermal model tab, which design can be observed in the Appendix A4.

There are also nine others supportive tabs named as: 1.0. Gas Conductivity, 1.1. T. Convection, 2. T. Radiation, 3. Temperature import, Coefficients, V3_Open, V3_Closed, V3_Mean and Copper plate.

Specific heat losses are calculated in associated tab and further called by "*IF*" function and calculation index match for actual application. Particular tab design is described in *7.2.2 Thermal model calculation procedure*.

7.2.1 Input parameters

Simulations include different variations of thermal loads and temperatures in accordance with Qualification Block tests. On the other hand, specimen & assembly construction related parameters remain the same. The input parameters are selected in the roll down menu, and include:

Fill the input parameters:			
Input Power		*4*	W
Cold Interface Temp. (CI,T4)		*-15*	°C
Experiment pressure		*0,001*	Pa
Gas type		*AIR*	[-]
Ambient Temperature		*11*	°C
Specimen type & ID		*V3 CLOSED*	0,1
Calculation Values:			
Input Real		4	W
Calculation index		-10,9	[-]
Gas thermal conductivity		0,0001	W/mK
Specimen Properties:			
Cylinder 1 diameter	D1=	45,70	mm
Cylinder 1 height	H1=	3,00	mm
Cylinder 2 diameter	D2=	21,50	mm
Cylinder 2 height	H2=	20,20	mm
Overall specimen height	L=	26,20	mm
Emitting area	A=	0,0022	m2
Contact surface	S=	1547,2	mm2
Spec. Material emissivity	ε=	0,10	[-]
Thermal Conductivity	λ=	62,0	W/mK
Specimen Conductance	C=	1,01	W/K
Specimen Resistance	R=	0,99	K/W

Figure 7.3: *Thermal Model v1.0 - input parameters*

- Input power
- CI (TC4) temperature
- Ambient gas pressure
- Gas type
- Ambient temperature ($T_{amb.}$)
- Specimen type

Other input parameters are derived from the construction parameters, geometry properties and physical constants. These inputs are however edited automatically with the roll down menu selection completion. Adjustable experiment conditions are indicated by purple text color and can be observed in Figure 7.3 along with complete Thermal Model input menu.

Thermal model v.1.0 is prepared for the test Block I evaluation. Experiment conditions section are limited in accordance with the designed test Block suitability.

7.2.2 Thermal model calculation procedure

The mathematical model primary serve as a heat losses calculator. Thermal loads, ambient conditions, and specimen conductance changes should result in different thermal losses of the whole assembly. The calculations rely on influencing phenomena quantification and further distribution.

The earlier mentioned heat losses are firstly calculated from the initially set parameters in associated software tabs. Once heat leakages are determined for the specific case, they are applied according to the scheme in Figure 7.1.

Power drops are then calculated based on specific assembly layer heat losses. A specimen conductance evaluation is done automatically based on calculated input parameters. The Thermal Model v1.0 evaluation process is further described in six main steps.

1. Convection quantification

Heating of the assembly resulted in pressure increase in previous experiments done by Jakub Mašek. The idea was that the heated gas would cause convection, resulting in potential pressure growth measured in Pirani gauge placed at the top of HST Chamber. During the HST Chamber Version 3 system tests, interface the heating effect experiment was performed to confirm the original idea. Temperature growth clearly implied a pressure increase measured with the newly installed WRG at the top of the V3 HST Chamber as well. Therefore, since both experiments recorded Medium vacuum (± 50 Pa) pressure increase while heating the interfaces, potential convection heat loss should be established.

Initial gas thermal conductivity determination is necessary to be able to proceed with specific assembly layer convection quantification for Block I cases. Gas thermal conductivity is evaluated in the first tab of the Thermal Model "*1.0. Gas Conductivity*". Molecular conditions were indicated in the system with pressure of 10^{-3} Pa, since the calculated Mean free path of molecules was a lot higher than the linear dimension of the system itself. [10] Therefore, gas thermal conductivity had to be recalculated for low pressure area implementing molecular conditions behavior of gases. Low pressure thermal conductivity is finally calculated as: [10]

$$\lambda = \frac{3}{8} \cdot \frac{\bar{v}}{T} \cdot \left(\frac{\alpha_E}{2 - \alpha_E}\right) \cdot d \cdot p \tag{6}$$

For the 50 Pa pressure environment, molecular behavior was not confirmed. Gas thermal conductivity is than determined from the following equation: [10]

$$\lambda = \frac{3}{4} \cdot \frac{\bar{v}}{T} \cdot p \cdot \bar{l} \tag{7}$$

Actual Thermal convection evaluation done in the second tab (*1.1. Thermal convection*) outsourcing the associated gas conductivity previously calculated in tab 1. The final equation describing the specific layer convection loss is then: [11][12]

$$Q_{Ki} = \alpha \cdot \Delta T \cdot S \tag{8}$$

Such a calculation runs for each Input power & CI (T4) Temperature combination – Calculation Index. Results are called based on selected scenario conditions, therefore input parameters & calculation index match. Particular assignment and further processing is done in a Thermal Model window.

2. Radiation quantification

Thermal radiation of the assembly parts are calculated separately, further applied to the original source part. In low pressure environment, radiation from thermally loaded assembly surfaces causes significant heat losses. Complete calculation of heat balance is presented in the *2. T.*

Radiation tab. User-set ambient temperature and specimen radiation surface is sourced from the input menu. Layer temperatures are called from the *4. Temperatures import* tab.

Multi-layer thermal insulation was simulated by creating the resistance net, describing the surface and the space resistances in order to evaluate multiple thermal exchange between insulation & system layers. [11] Such a designed resistance net counts with multiple heat reflection and outputs the final surfaces heat exchange value. The resistance net for heat balance between the insulated assembly and the HST chamber can be observed in Figure 7.4.

$$Q_{1\text{-}2}=\frac{\sigma\cdot S_1\cdot\left(T_1^4\text{-}T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1\cdot S_1}+\frac{1}{S_1\cdot F_{1\text{-}2}}+\frac{1-\varepsilon_2}{\varepsilon_2\cdot S_2}+\frac{1-\varepsilon_2}{\varepsilon_2\cdot S_2}+\frac{1}{S_2\cdot F_{2\text{-}3}}+\frac{1-\varepsilon_3}{\varepsilon_3\cdot S_3}} \tag{9}$$

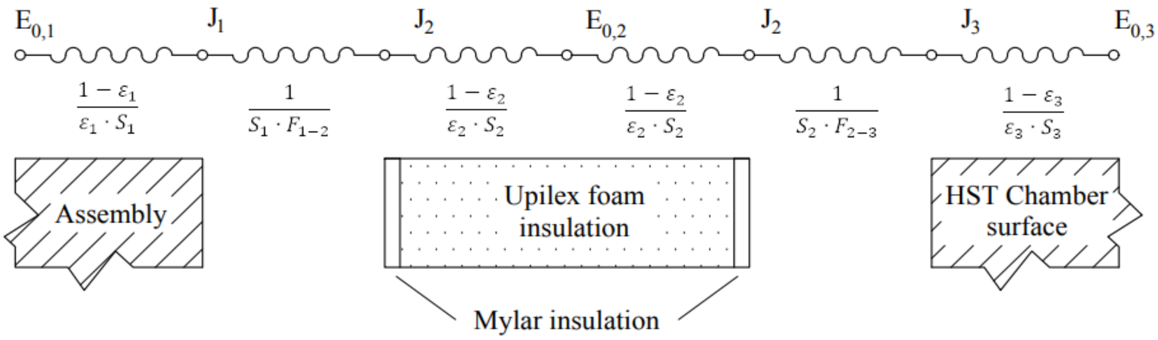

Figure 7.4: *Thermal insulation emissivity influence determination.*

In reverse, HST chamber radiation was taken into account for a cooler assembly case as well. However, the final heat balance is established in step *4. Losses distribution & application*.

3. Real heat input determination

Input heat Q [W] is a preset value which can be adjusted on the HI DC Power supply. Newly installed HI power source secures appropriate power input to the heating resistors. Current settings values of the common Block I input powers was covered in *4.2 Input parameters.* However, any input power can be achieved by specific power source settings, considering:

$$I_{set}=\sqrt{\frac{Q_{1intended}}{8}}$$

Others layer input heat loads have to be determined separately. Specific heat input values can vary depending on actual layer temperature, therefore heat lose/intake balance caused by layer thermal resistance, thermal contact resistance, radiation and gas influence – convection. Evaluation of mentioned heat loses is kay for further specimen / MHS conductance determination. It is obvious $Q_{real\text{-}in} = Q_{max} = Q_1$ in assembly hot case. Moreover, hot case is represented by the following equation:

$$Q_1\ (=Q_{real\text{-}in}) > Q_2 > Q_3 \tag{10}$$

While the assembly cold case (heat losses of HST Chamber are accepted by the assembly) could be described as:

$$Q_1\ (=Q_{real\text{-}in}) < Q_2 < Q_3 \tag{11}$$

The real heat input power establishment can be observed in the actual Thermal Model tab, in the Input menu window, so the user has a clear view on the necessary simulation entry parameters.

Note: *Also, another combinations are possible if the assembly temperature is not higher or lower as a whole.*

4. Losses distribution & application

Assembly layer input power Q_{in-i} is modified by its particular (previously calculated) heat balance value. The heat can be lost or accepted as mentioned before. Such an adjusted input power is further considered to be an output parameter of the particular assembly part. Heat balance assignment simulates the heat transfer through the measurement system affected by excepted heat loses.

Based on i-layer and ambient temperature comparison, one of the following equations is used for Q_{out-i} establishment:

Assembly layer is hotter than the ambient gas

$$Q_{out-i} = Q_{in-i} - K_i - R_i \tag{12}$$

Assembly layer is colder than the ambient gas

$$Q_{out-i} = Q_{in-i} + R_i + K_i \tag{13}$$

Where $i = 1, 2, 3, 4, 5$

Final Q_{out-i} is also next layer power input value Q_{in-i+1} ($Q_{out-i} = Q_{in-i+1}$) further processed in the same way as previous Q_{in} variables.

5. Thermal contact resistance quantification

TCR between two assembly layers depends on physical properties. Since the HI-Hot Cpper plate & Hold Copper plate-CI contact surfaces and materials are the same, it is believed also the TCR would be the same ($TCR_1 \approx TCR_4$). Although exact TCR value is unknown, it was determined as a reversed thermal conductance according the following equation:

$$TCR_1 = \frac{(T_2 - T_1)}{Q_{out\ 1}} = TCR_4 \tag{14}$$

Contact resistance between copper plates and the Specimen should be the same based on the previously mentioned assumption ($TCR_2 \approx TCR_3$). However, the temperature difference is measured among both copper plates which involves resistances: TCR_2, Specimen thermal resistance and TCR_3. The final TCR_2 ($\approx TCR_3$) value has to be decreased by the thermal resistance of the actual Specimen:

$$TCR_2 = \frac{\left(\frac{(TC_{2,7} - TH_{2,7})}{Q_{out\ 2}} - R_{SPCM}\right)}{2} = TCR_3 \tag{15}$$

Real TCR values should be imported as constants in order to evaluate the MHS conduction. Particular Calculation index-associated TCR values are gathered for further processing. It is believed, calculated values would be representative enough once sufficient amount of measurements is evaluated. Constant TCR values should be involved in Thermal Model v1.1.

6. Q_{out4} determination

In order to preserve the TCR_4 & TCR_1 equal values, Q_{out4} has to be adjusted. Actual TCR_4 calculation remain the same, however resistance input power has to be determined as:

$$Q_{out4} = \frac{\Delta T_3}{TCR_1} \tag{16}$$

Such a calculated Q_{out4} also indicates cumulated heat loss which should be assigned to assembly layers (*i = 1, 2, 3, 4*). In the optimistic case the calculated Q_{out4} value is equal to particular Q_{in4}. Meaning, the calculated heat loses are in conformance with the assumed cumulated value. Otherwise, the layer specific heat loses values must be added to recalculated Q_{out4} in order to get the original Q_{in4}. The procedure causes a power difference between Qout3 and Q_{in4}. Calibration of the heat loses determination is then required to harmonize the difference. The calibration process is further described in the *6.3 Calibration data*.

7. Conductance calculation

The final specimen Conductance C [W/K] is evaluated from the adjusted input power values (affected by heat loses) and measured temperature differences. Specifically, Specimen conductance would be calculated as:

$$C_{SPCM} = \frac{Q_3}{\Delta T_2} \tag{17}$$

Steps 3 to 6 are done in the Thermal Model tab. Calculated conductance is expected to be lower than the original specimen one. However, knowledge of the heat losses in assembly layers should provide measurement coefficients, which would bring the confidence into the further simulation process.

A set of different coefficient for Block I, Block II and Block III is expected due to different input parameters. Test relevant coefficients are to be further applied in EQM phase as a test facility error correction.

7.2.3 Thermal model evaluation window

Evaluated measurement is presented in a schematic Evaluation window in *Thermal Model* tab. Assembly layers color indicates particular assembly temperature. Warm colors were chosen for “hot” case (specific layer is warmer than ambient temperature), while the cold case is represented by green, grey and blue color depending on its actual temperature. The visualization then allows fast and intuitive hot & cold case determination, therefore overall heat losses distribution. The actual Evaluation window can be observed in Figure 7.5.

Layers information

Five assembly layers also shows some of the layer associated features. Assembly layers are identified at bottom left corner of the schematic part picture. Layer specific temperature is located at the place of actual temperature probes. Therefore, measured temperature differences ΔT1, ΔT2, ΔT3 are clearly defined as well. The final Specimen / Copper plate thermal conductance is presented at the center.

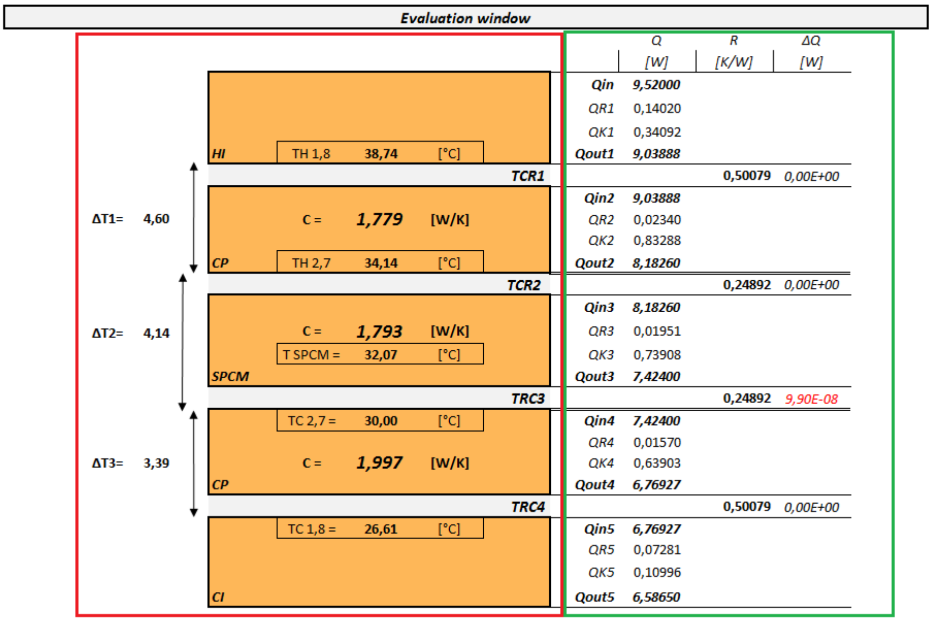

Figure 7.5: Thermal Model Layers information & Evaluation parameters.

Evaluation variables

The green section on the right of the layer schematic presents the heat evolution. Heat loses affect the input and output power values $Q_{in\ i}$ and $Q_{out\ i}$. Thermal radiation (Q_{Ri}) and thermal convection (Q_{Ki}) values are red whenever the heat loss of the HST Chamber is bigger than heat loss of the assembly. Calculated TCR values are indicated in third column.

7.3 Calibration data

The Q_{out4} recalculation mentioned in the step 6 of Thermal model calculation procedure can cause inequality between Q_{out3} & Q_{in4}. Positive power difference ΔQ (Q_{out}-Q_{in}) reflects the calculated heat losses are lower than assumed. On the other hand, a negative difference indicates thermal radiation and convection to be higher. The power difference can be found in the fourth column of the Evaluation window, described earlier.

Heat loses calculations can be regulated by potentially inaccurate parameters adjustment. The evaluation process involves experimentally established variables such as: heat transfer coefficient *h* [W/m^{2}K][10], assembly parts emissivity *ε* [-][13] and Thermal Contact Resistance *TCR* [K/W]. The values are however determined based on assumed or available average values in accordance with the physical laws. Exact definition of mentioned parameters would improve the evaluation procedure and results. The Calibration position within Thermal Model v1.0 can be observed in Figure 7.6.

Note: *TCR causes the temperature difference among the assembly layers. Therefore, TCR does not affect the heat loses values at all and must be refined otherwise.*

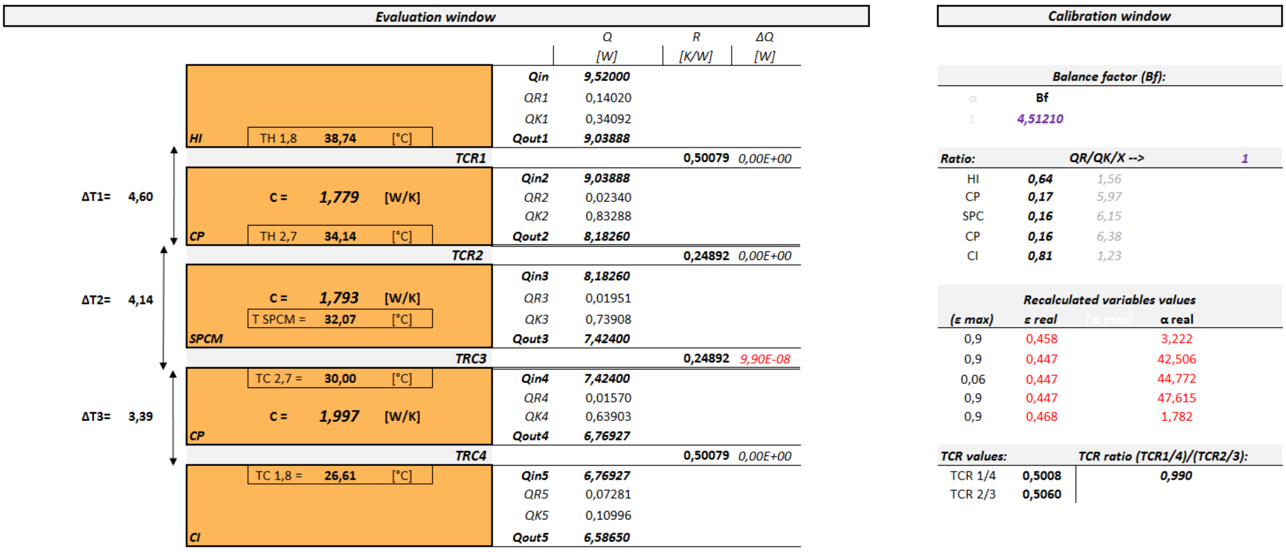

Figure 7.6: *Evaluation & Calibration window showcase. The Balance factor input is in top right corner.*

It is possible to harmonize Q_{out3} & Q_{in4} by proper tuning of the balance factor (Bf). Rising of the Bf increases the heat loses in the preserved ratio. Manual adjustments are done in Calibration window next to Evaluation Window in Thermal Model tab. The goal is to scale down ΔQ till the difference is very small rather than negligible. Emissivity and heat transfer coefficient are then recalculated backwards, based on the increased heat loss value. Modified variables values should be within physical conditions range. Since the emissivity can not be higher than 1 ($\varepsilon < 1$), recalculated results presented in the Recalculated values box must be checked. Heat transfer coefficient extreme is not clearly defined as it depends on many factors.

The final calibration data are composed of recalculated: α, ε and TCR associated with the actual Calculation index. Multiple evaluation results should be gathered in order to create a complex database of the calculated values. Collected data are to be further processed based on the relations between observed variables and experiment conditions.

The refining procedure should outcome a constant calibration parameters which can be later involved in the Thermal Model v1.1 evaluations. Once the refined calibration data are included in the enhanced Thermal Model version, a simulation of the upcoming Specimen measurements can be done. Such a prediction would be then compared with the actual experiment results. Therefore, the final Calibration coefficients definition would be possible after the simulation and measurement outputs harmonization. Any inequality should result the calibration constants adjustments/redefinition.

A complete calibration coefficients determination process breakdown can be observed in Figure 7.7. At the actual calibration phase, initial 3rd generation Specimen measurements results should be imported to the Thermal Model v1.0 in order to expand the current functionality.

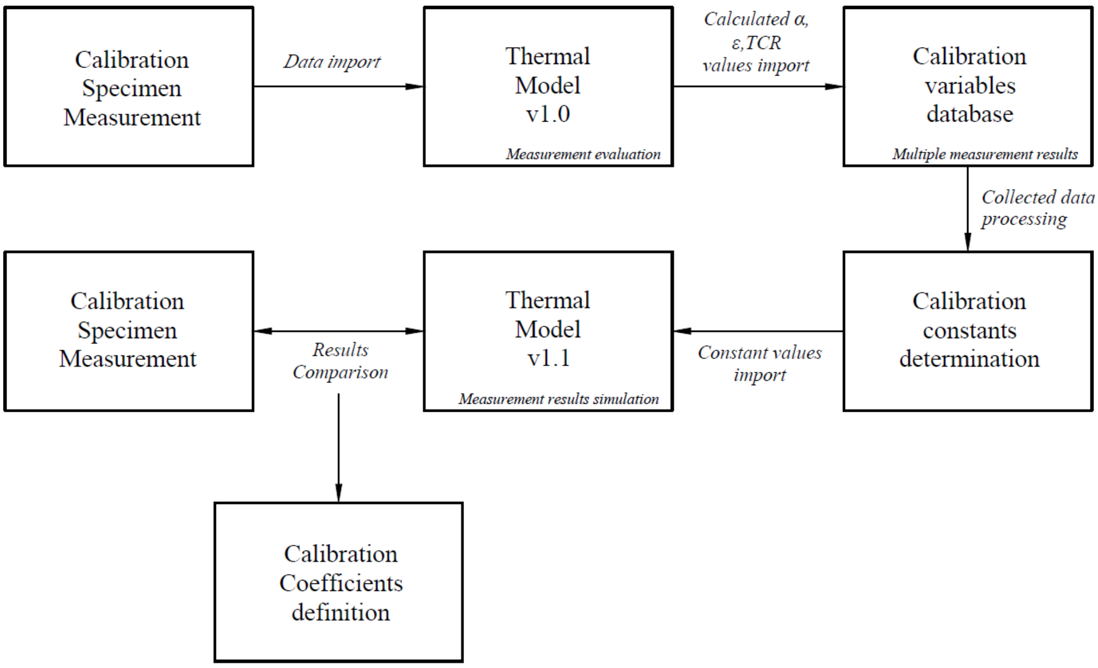

***Figure** 7.7: Thermal Model v1.0 refining process breakdown.*

8 CALIBRATION SPECIMENS MEASUREMENT

One test was planned for each 3rd generation dummy specimen. The test is composed of multiple events with different combinations of the measurement settings. Generally, one event covers a particular combination of input power & T4 temperature. Specimens thermal resistances were considered while designing the Test plan, in order to secure the maximal assembly temperature lower than 60 °C. The final test plan is presented in the Table 8.1.

Table 8.1: *V3 Dummies Test plan. The plan describes particular measurement conditions within the test.*

Calibration measurement Test Plan						
Calibration Specimen	**Test No.**	**T4 Constant [°C]**	**Q_{in1} [W]** ***2***	**Q_{in1} [W]** ***4***	**Q_{in1} [W]** ***7***	**Q_{in1} [W]** ***10***
V3 Dummy Closed	30012	***-15***	✓	✓	✓	
		0		✓	✓	
		15		✓		
		30				
V3 Dummy Mean	30013	***-15***	✓	✓		
		0		✓		
		15	✓	✓		
		30				
V3 Dummy Open	30014	***-15***	✓			
		0	✓	✓		
		15	✓			
		30				

Note: *Constant pre-set input power delivery is achieved by setting theoretically unreachable temperature on HI Temperature Regulator. However, the maximal temperature set on the HI Regulators can not overlap 60°C, which could cause melting of the glue.*

8.1 General test experiment conditions

The 3rd generation dummies test design was in conformance with Block I input conditions. The measurements were performed under minimal pressure possible. The aim of the test was the same within all the tests:

Aim of the test

Measure the Specimen conductance. Determine the temperature differences ΔT1, ΔT2, ΔT3. Evaluate the results using both the original HST Chamber V2 and the Thermal Model evaluation methods. Gather the Thermal Model variables values if possible.

Test facility	HST Chamber version 3
HI Input power	2, 4, 7, 10 W
T4 constant temperature	-15, 0, 15, 30 °C
Inner gas:	Air
Inner pressure:	≈ $2 \cdot 10^{-5}$ mbar
Specimen:	Dummy 3rd generation
Specimen Insulation	Yes

8.1.1 HST Chamber V3 System settings

HST Chamber V3 general settings were established during the initial system tests.

Inner gas:	Air
WRG position:	Bottom
WRG Gas Type	N_2 (TIC settings)
Graphite foils:	No
Weight:	No
Copper Belts:	No
Regulators:	HI: Yes
	CI: Yes
Temperature probes:	14 + 2
Temp. probes recording:	TH 2, 3, 4, 6, 7, 8, 9
	TC 2, 3, 4, 6, 7, 8, 9
Temp. Controllers input:	TH 5, TC 5

8.1.2 Test procedure

A generalized Test procedure is presented. The power source and the temperature controllers adjustments were required in accordance with the particular event conditions. The specimen exchange can also be skipped while performing the events within the same test number. View the Appendix A5 for the specimen exchange documentation.

A. Specimen Exchange
   1. Remove the top flange and open the inspection window
   2. Pull out the: weight, HI, Copper plates (+Specimen)
   3. Screw down the Cold Copper plate (bottom) and the V3 Dummy Specimen
   4. Place insulation around the Copper Plate & Specimen
   5. Put the Hot (top) Copper plate on the top of the Specimen
   6. Place the Insulated Copper plate-Specimen assembly through the Inspection window on the CI inside of the chamber
   7. Lay the HI with weight pad on the Hot Copper Plate
   8. Place the weight on the weight pad
   9. Close the Inspection window and the top flange

B. Turn on DAU ESAM
C. Create the high air vacuum environment (refer to ***Chyba! Nenalezen zdroj odkazů. Chyba! Nenalezen zdroj odkazů.*** procedures)
D. Start the desktop acquisition application, mark the Event start
E. Set Temperature regulators (in conformance with actual Test number & event settings)
F. Set the power source output (in conformance with actual Test number & event settings)
G. Turn on the power sources once the measurement pressure is reached
H. Maintain T4 constant temperature within 0.5 °C range
    - Add LIN to the CI LIN storage whenever needed
I. Record the steady state of the assembly
J. Mark the Event end whenever the steady state is reached
K. Stop the acquisition once the measurement is done
L. Turn off the vacuum pump
M. Turn off the DAU ESAM, power sources, temperature controllers

Note: *Let the system cycle on during the experiment to reach the exclusive pressure.*

8.2 V3 Dummy Closed Block 1

Dummy Specimen V3 Closed Block 1 test: 30012_CB1 (Test No. 30012) was divided into six events in total. The design of particular event measurements can be observed in Table 8.2.

Table 8.2: *Test Number 30012 specific Event conditions breakdown.*

Test No. 30012			
Events / date	**Input power Q_{in1} [W]**	**T4 temperature T_4 [°C]**	**CI Power source I [A]**
Event 1 (6.5.2019)	2	-15	0.5
Event 2 (6.5.2019)	4	-15	0.707
Event 3 (6.5.2019)	7	-15	0.935
Event 4 (6.5.2019)	4	0	0.707
Event 5 (7.5.2019)	7	0	0.935
Event 6 (7.5.2019)	4	15	0.707

Test description:

Following the general Test Procedure instructions, specific Event settings were required. HI voltage adjustments on the HI Power Source were done, so the output current corresponded with the needed value. HI Temperature regulator was set to 58 °C during all the events.

Test results:

A steady state of all measured events was reached and recorded. The temperature difference among the Copper plates was higher than expected based on the specimen designed conductance.

The measurement outputs evaluated in the Thermal Model provided more consistent outputs. However, the calculations assumed the radiation and convection heat losses to be equal. The emissivity and heat transfer coefficient were retroactively recalculated from the determined heat losses to confirm the physical correctness. Both of the values were found to be within the limiting range through the performed measurement. The Thermal Model evaluation was possible thanks to ambient temperature knowledge & calculation involvement.

The Thermal Model refining process should include clearly determined heat losses ratio, so the particular losses can be spread according assumed general rule. The test results are presented in Table 8.3. below, where the final conductance evaluated with the original V2 method is indicated as a C_{V2} while the Thermal Model approach as C_{TM}. The actual Events progression can be observed in Figure 8.1. The chart covers the whole V3 Dummy Closed test.

Table 8.3: *Test Number 30012 Measured & Evaluated results.*

Event inputs			Measured parameters				Evaluated values	
Event	**Q_{in1} [W]**	**T4 Temp. [°C]**	**ΔT1 [°C]**	**ΔT2 [°C]**	**ΔT3 [°C]**	**T amb. [°C]**	**C_{V2} [W/K]**	**C_{TM} [W/K]**
Event 1	**2**	**-15**	2.47	15.18	2.89	11	0.240	*0.135*
Event 2	**4**	**-15**	4.44	27.02	5.20	11	0.127	*0.148*
Event 4		**0**	3.81	24.89	4.61	16	0.141	*0.158*
Event 6		**15**	3.75	22.21	4.11	20	0.083	*0.217*
Event 3	**7**	**-15**	6.89	44.32	8.76	11	0.079	*0.156*
Event 5		**0**	6.65	40.21	7.82	14.5	0.151	*0.171*

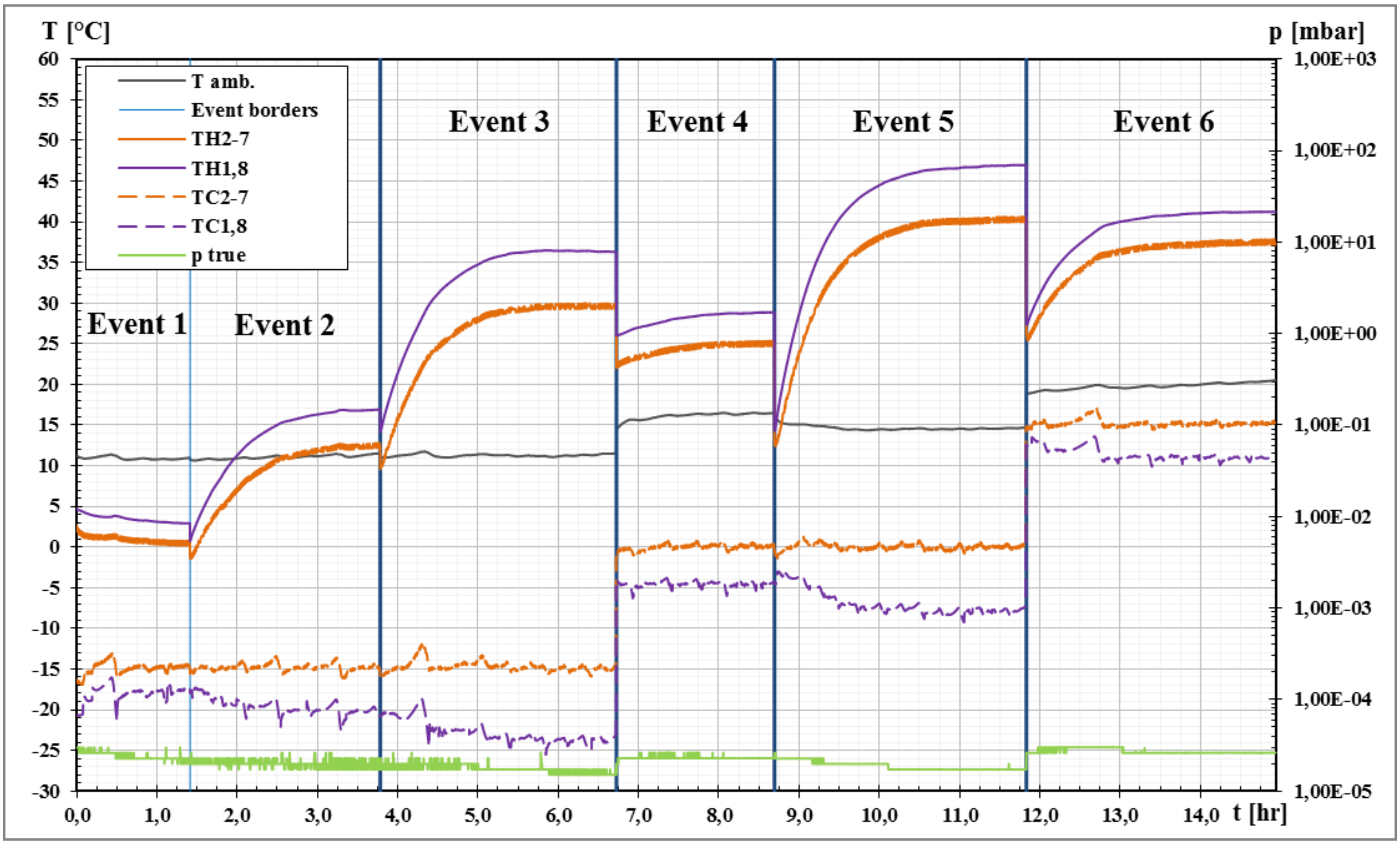

Figure 8.1: *Event evolution within the test. Constant TH2-7 & TH1,8 temperatures indicate a steady state.*

8.3 V3 Dummy Mean Block 1

The 30013_MB1 test included 5 events further specified in Table 8.4 below.

Table 8.4: *Test Number 30013 Event input conditions settings breakdown.*

Test No. 30013			
Events / date	**Input power Q_{in1} [W]**	**T4 temperature T_4 [°C]**	**CI Power source I [A]**
Event 1 (7.5.2019)	4	15	0.707
Event 2 (7.5.2019)	2	15	0.5
Event 3 (8.5.2019)	4	0	0.707
Event 4 (14.5.2019)	2	-15	0.5
Event 5 (14.5.2019)	4	-15	0.707

Test description:

The events 1 & 3 had to be terminated before reaching the steady state. TH 4 temperature initiated the occasional shutdown of the HI Power source. Therefore, committed test conditions were not fulfilled in such a cases. Increasing of the HI Temperature Controller set temperature would cross limit value.

Test results:

The specimen conductance could not be evaluated in the Events 1 & 3 since the steady state was not reached. However, the other cases were evaluated within the Thermal Model as well.

The calculation tuning was exceptionally successful in the Event 2. Balance factor setting allowed to harmonize the Q_{out3} and Q_{in4} values. At the same time, the recalculated variables values were within assumed limits.

Although the values evaluated in Thermal Model were more consistent, the original method provided better results in Events 2 & 4. In comparison to V3 Mean designed conductance (0.2 W/K) the Event 2 & 4 outcomes were more accurate. The results are presented in Table 8.5 and Figure 8.2.

Table 8.5: *Test 30013 Measured & Evaluated values.*

Event inputs			Measured parameters				Evaluated values	
Event	**Q_{in1} [W]**	**T4 Temp. [°C]**	**ΔT1 [°C]**	**ΔT2 [°C]**	**ΔT3 [°C]**	**T amb. [°C]**	**C_{V2} [W/K]**	**C_{TM} [W/K]**
Event 4	**2**	**-15**	3.06	31.21	2.53	14	0.240	*0.064*
Event 2		**15**	1.78	22.66	1.63	22	0.201	*0.067*
Event 5	**4**	**0**	5.31	53.83	4.40	15	0.077	*0.087*

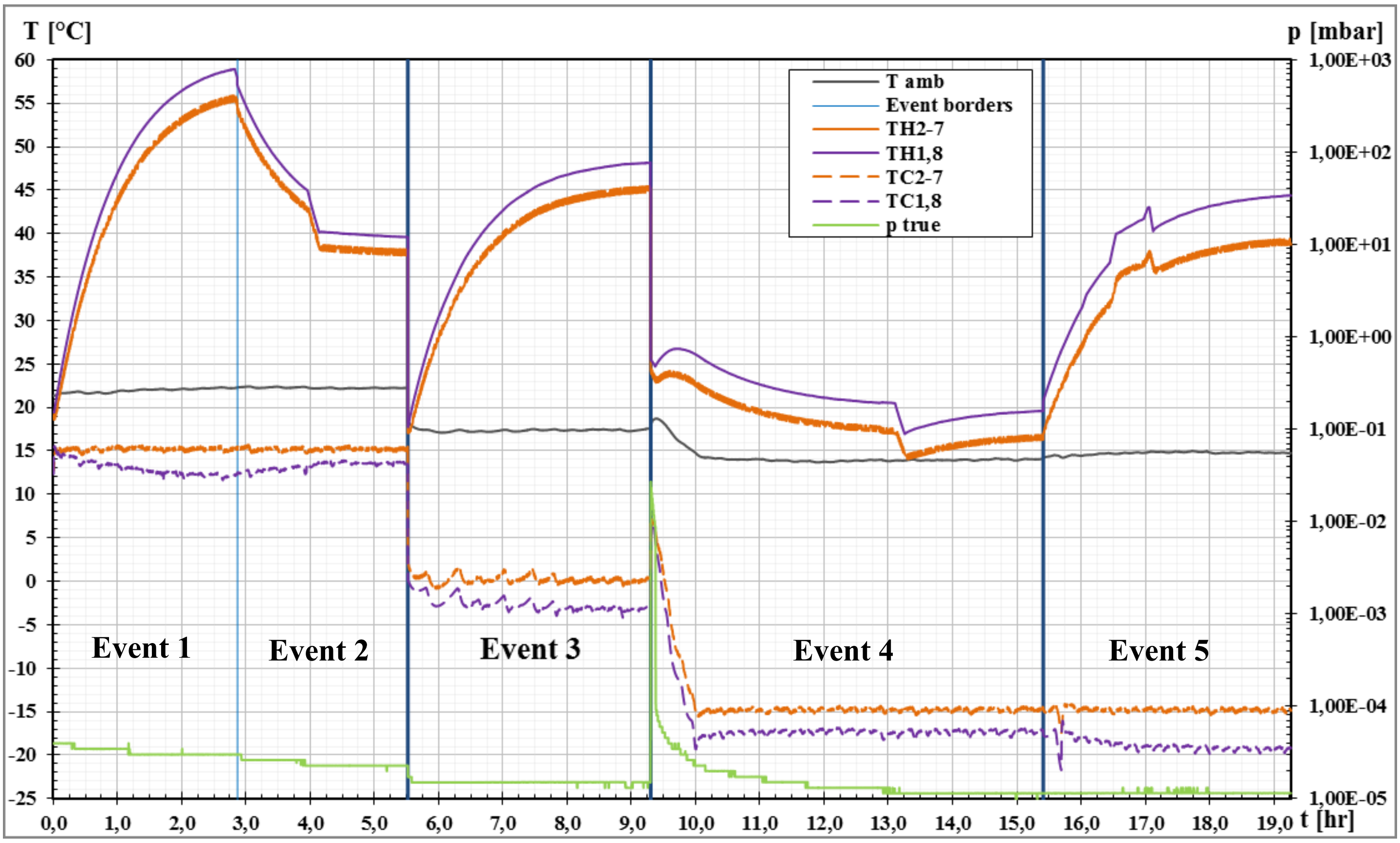

Figure 8.2: *Test Number 30013 Events record.*

8.4 V3 Dummy Open Block 1

It was assumed that high thermal resistance of the V3 Open could cause the overheating of the HI. Therefore, the lowest input power & temperature combinations were drafted for the 30014_CB1 test as can be seen in Table 8.6.

Table 8.6: *Test Number 30014 Events.*

Test No. 30014			
Events / date	**Input power Q_{in1} [W]**	**T4 temperature T_4 [°C]**	**CI Power source I [A]**
Event 1 (9.5.2019)	2	15	0.5
Event 2 (10.5.2019)	2	0	0.5
Event 3 (10.5.2019)	2	-15	0.5
Event 4 (14.5.2019)	4	0	0.707

Test description:

The steady state was not reached in any event within V3 Open dummy. All the measurements had to be terminated prematurely due to limiting hot side temperature growth.

A wrong pressure indication occurred during the Events 2, 3 & 4. The automatic Calibration command was not sent through TIC – Gauge settings before the experiments. However, it is believed the inner pressure was within usual range since the Turbo pumping station was working correctly.

Test results:

The Specimen conductance was not possible to evaluate based on the performed measurements. High resistive specimen completely insulated both Hot & Cold Interfaces within the measurable temperature range. However, events progression is presented in Figure 8.3.

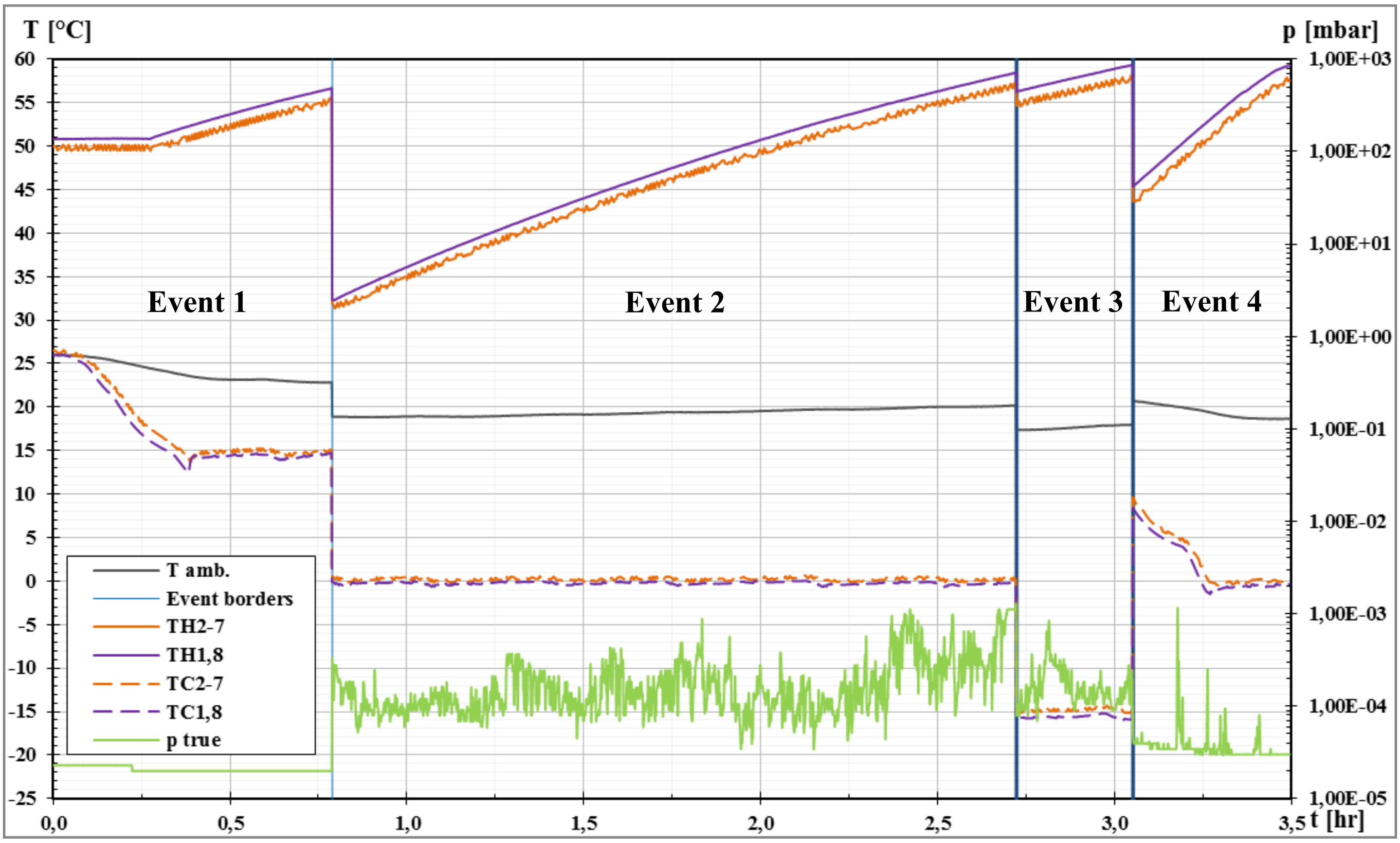

Figure 8.3: *Test 30014 Events record. Hot side temperatures are clearly increasing over 60 °C.*

9 CALIBRATION MEASUREMENT ANALYSIS

Fourteen 3rd generation Dummies experiments were performed under modified Block I conditions within three specimen tests. For the first time, the specimen´s conductance was measured under high vacuum environment.

The ability to reach a steady state during the low conductivity Specimens experiments was strongly reduced due to maximal temperature limitation. The initial Thermal Model v1.0 evaluation results should serve for the future refining process.

9.1 Thermal Model v1.0 evaluation

The Thermal Model v1.0 evaluation method performed well in comparison with the originally used evaluation approach. The consistent model results indicates the core procedures are designed correctly. However, the calculated heat losses values should not be presented as final, since the actual radiative & conductive losses ratio must be determined first.

Backward recalculation results of the experimentally assumed variables turned out to be within a physically defined limits. Also the evaluated specimen´s conductance was higher while measuring the more conductive specimen. These facts confirms the calculation correctness in general.

The method relies on the ambient temperature knowledge. Therefore, the heat losses calculations were functional once an average inner temperature was filled in. The inner chamber temperature ($T_{amb.}$) was recorded by the unfixed loosely laid probe TH9 placed at the bottom of HST Chamber.

TCR 2 & 3 values were surprisingly higher than expected. The exact TCR´s values are one of the necessarily required Thermal Model refining parameters.

9.1.1 Objects of possible improvements

The calibration specimen measurements provided an information about the overall Thermal Model v1.0 functionality. However, some of the improvement areas were defined based on the results. The updated version of the model should provide a solutions for:

- Thermal Radiation / Thermal Convection heat loss ratio
- TCR values determination
- Actual material thermal conductivity (specimen conductance)
- Actual Specimen & Measurement assembly emissivity
- Actual Specimen & Measurement assembly heat transfer coefficient

From now on, the measurements should involve the ambient temperature recording. The HST Chamber inner temperature knowledge is absolutely key in defining the heat losses through the mathematical model.

10 CONCLUSION

Recovering of the Heat Switch test Chamber required a great effort while implementing the upgrades. The first system tests performed with a new vacuum pump installed recorded an exceptional results with a $1\cdot10^{-4}$ mbar pressure reached. Vacuum with such parameters had not been experienced before in the MHS project. Environmental limits were even pushed further during the final measurements, where the pressure reached was within the Qualification test conditions, specifically $1\cdot10^{-5}$ mbar. Sufficient HST Chamber tightness was proved while performing the CO_2 cycles as part of the Martian atmosphere creation. Established system operations were covered in the Test & particular environment settings procedures. The HST Chamber version 3 commissioning was finished with the inner thermal insulation renewing. A brand new specimen insulation coating was prepared out of Upilex foil & foam using a Mylar foil and PTFE tape as well. Hot & Cold Interfaces insulations were restored too.

Three 3rd generation Dummies were designed to simulate three of the potential MHS states. A material selection was the key in defining the final specimens properties, especially than thermal conductance. Bronze has been chosen for the specimens representing closed and mean MHS state with the conductance 1.0 and 0.2 W/K. On the other hand, thermal resistive PTFE was used to achieve 0.016 W/K conductance for MHS open position simulation. Unlike in the 2nd dummy generation, the depressuring groove and screw pads were added in the bronze specimens design. It is believed that the modification should secure proper depressuring of the dummies middle sections as well as a surface contact improvement thanks to screw joints. The created CATIA models can be reused in the thermal/fluid simulation software for the further analysis.

The Thermal Model v1.0 has been presented as a new HST Chamber measurements evaluation method. The method was defined after the inside chamber thermal processes analysis & specification. The evaluation relies on the heat losses determination and quantification. Although the losses calculations involves some of the necessarily assumed values, the specimen conductance was possible to be determined.

A total of 15 measurements were performed within three 3rd generation dummies tests. Each of the specimen test was divided into several events representing different measurements conditions. The specimen conductance was determined using the original HST Chamber version 2 evaluation process. However, the measurement results were also imported to the Thermal Model v1.0 in order to compare the evaluation outcomes. Both evaluation methods provided similar results in most cases. Therefore, the Thermal Model v1.0 can be considered as a solid basis for the future application.

Thanks to an optimistic Thermal Model v1.0 results, it is believed, the generalized HST Chamber calibration coefficients can be extracted from the enhanced Thermal Model v1.1 once a convenient amount of measurements is executed. The improvement will be done through the designed refining process, which will identify the assumed values with a sufficient confidence. The refined version should become a powerful tool in the Qualification tests evaluating, since it will be possible to predict the measurement results within the model simulation.

A coherent test facility performance description would be possible once the calibration specimen measurements results are in conformance with the actual Thermal Model v1.1 simulation. However, essential steps were executed in order to proceed with the Thermal Model v1.0 refining. The presented heat transfer understanding will be crucial for the following measurements and data evaluation.

In the past six months, the HST Chamber has been rebuilt into an improved version 3, capable of Qualification test conditions simulations. This document covers the solution for the final test facility calibration. The initially set requirements of the thesis were fulfilled and the outcomes will serve in the future MHS project progression. It is believed that the calibration process will be definitely accomplished through the endeavors of the MHS project team.

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12 LIST OF ABBREVIATIONS

AITP	Assembly, Integration and Test Plan
AR	Acceptance Review
BB	Bred Board
BUT	Brno University of Technology
C&S	Customer & Supplier
CDR	Critical Design Review
CI	Cold Interface
CT	Calibration Test
DAS	Data Acquisition System
DC	Direct current
ECSS	European Cooperation for Space Standardization
EQM	Engineering Qualification Model
ESA	European Space Agency
FFT	Full Funcitional Test
HI	Hot Interface
HST	Heat Switch Test (chamber)
IAE	Institute of Aeronautical Engineering
LIN	Liquid Nitrogen
MHS	Miniaturized Heat Switch
PC	Personal Computer
PT	Performance Test
PTFE	Polytetrafluorethylene, Teflon
PTR	Post Test Review
PU	Polyutethane
QR	Qualification Review
QT	Qualification Test
R&T&D	Research, Technology and Developement
RFT	Reduced Fuctional Test
STBY	Standby
TIC	Turbo & Instrument Controller
TN	Technical Note
TPRO	Test Procedure
TRB	Test Review Board
TRL	Technology Readiness Level
TRPT	Test Report
TRR	Test Readiness Review
TSPE	Test Specification
WRG	Wide Range Gauge

13 LIST OF FIGURES

14 LIST OF TABLES

15 APPENDIX

A1 – ECSS Tolerances & Accuracies

A2 – V3 Dummy Drawings

A3 – V3 CATIA models

A4 – Thermal Model v1.0 UI

A5 – Photo Documentation

Appendix A1 – ECSS Tolerances & accuracies

ECSS-E-ST-10-03C
1 June 2012

Table 4-1: Allowable tolerances

Test parameters	Tolerances
1. Temperature	Low High
above 80K	Tmin +0/-4 K Tmax -0/+4 K
T< 80 K	Tolerance to be defined case by case
2. Relative humidity	± 10 %
3. Pressure (in vacuum chamber)	
> 1,3 hPa	± 15 %
1,3 10-3 hPa to 1,3hPa	± 30 %
< 1,3 10-3 hPa	± 80 %
4. Acceleration (steady state) and static load	-0 / +10 %
5. Sinusoidal vibration	
Frequency (5 Hz to 2000 Hz)	± 2 % (or ±1 Hz whichever is greater)
Amplitude	± 10 %
Sweep rate (Oct/min)	± 5 %
6. Random vibration	
Amplitude (PSD, frequency resolution better than 10Hz)	
20 Hz - 1000 Hz	-1 dB / +3 dB
1000 Hz - 2000 Hz	± 3 dB
Random overall g r.m.s.	± 10 %
7. Acoustic noise	
Sound pressure level, Octave band centre (Hz)	
31,5	-2 dB /+4 dB
63	-1 dB /+3 dB
125	-1 dB /+3 dB
250	-1 dB /+3 dB
500	-1 dB /+3 dB
1000	-1 dB /+3 dB
2000	-1 dB /+3 dB
Overall	-1 dB /+3 dB
Sound pressure level homogeneity per octave band	+/- 2 dB
8. Microvibration	
Acceleration	±10 %

Figure 15.1: *ECSS Standard Test Tolerances pt.I.*

ECSS-E-ST-10-03C
1 June 2012

Test parameters	Tolerances
Forces or torque	±10 %
9. Audible noise (for Crewed Element only)	
Sound-power (1/3 octave band centre frequency)	
32,5 Hz - 160 Hz	±3 dB
160 Hz – 16 kHz	±2 dB
9. Shock	
Response spectrum amplitude (1/12 octave centre frequency or higher)	
Shock level	- 3 dB/ + 6 dB 50 % of the SRS amplitude above 0 dB
10. Solar flux	
in reference plane	± 4 % of the set value
in reference volume	± 6 % of the set value
11. Infrared flux	
Mean value	± 3 % on reference plane(s)
12. Test duration	-0/+10 %

Figure 15.2: *ECSS Standard Test Tolerances pt.II.*

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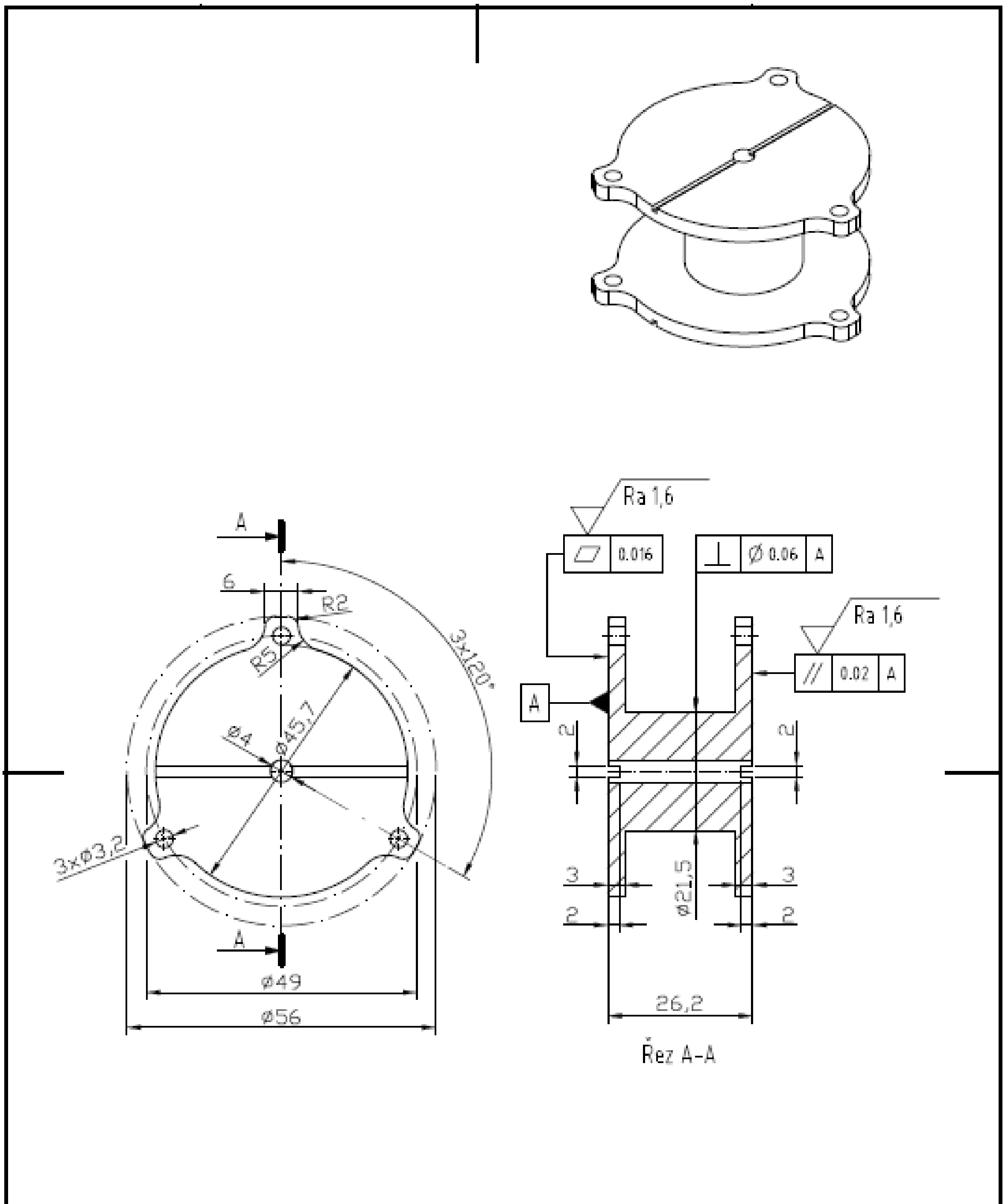
Table 4-2: Test accuracies

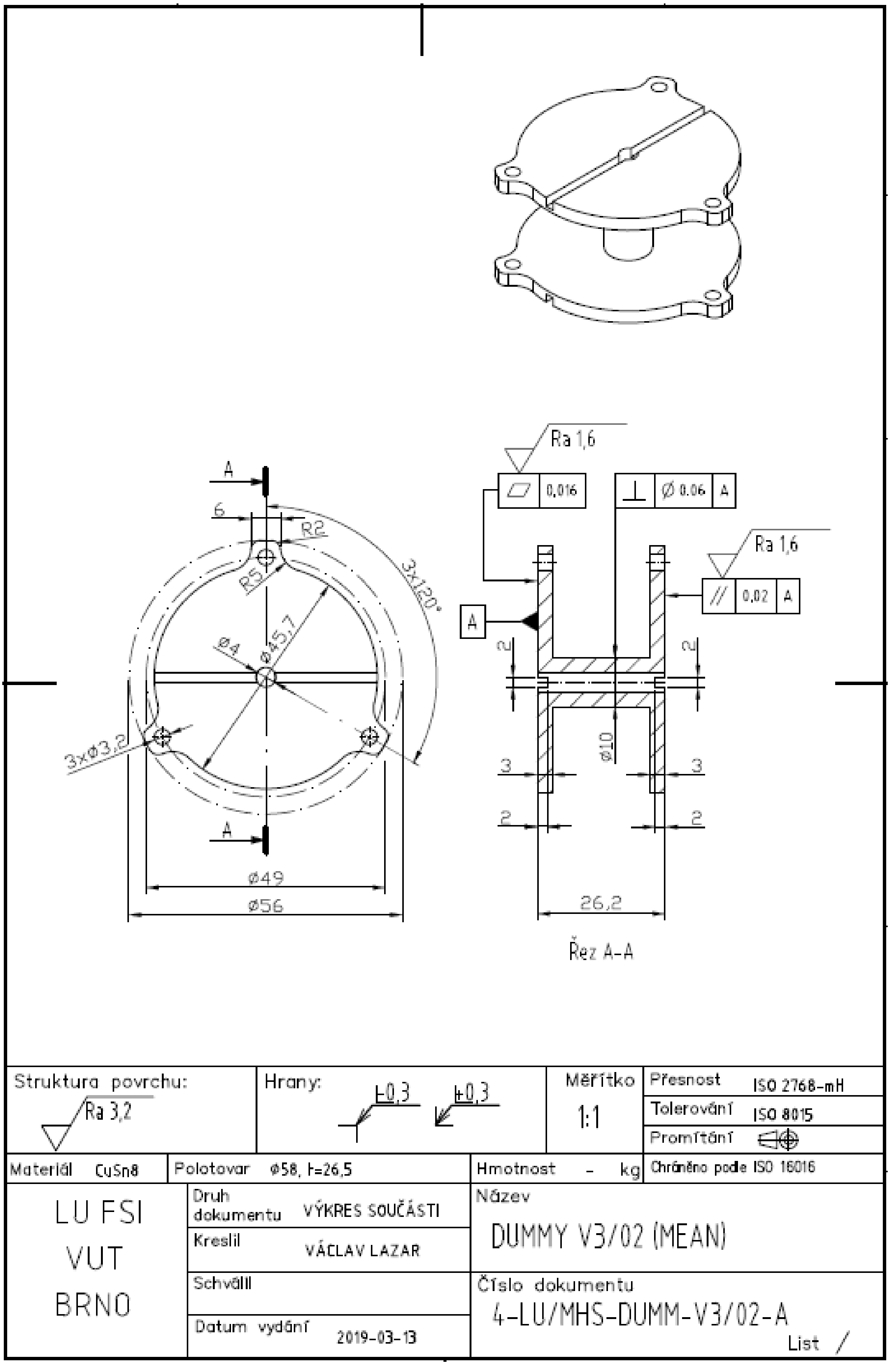
Test parameters	Accuracy
1. Mass	
Space segment equipment and space segment element	± 0,05 % or 1 g whatever is the heavier
2. Centre of gravity (CoG)	
Space segment equipment	Within a 1 mm radius sphere
Space segment element	± 2,5 mm along launch axis ± 1 mm along the other 2 axes
3. Moment of inertia (MoI)	
Space segment equipment and Space segment element	± 3 % for each axis
4. Leak rate	One magnitude lower than the system specification, in Pa m^3 s^{-1} at standard conditions (1013,25 Pa and 288,15 K).
5. Audible noise (for Crewed Element only)	
32,5 Hz to 160 Hz	± 3 dB
160 Hz to 16 kHz	± 2 dB
6. Temperature	
above 80 K	± 2 K
T< 80 K	Accuracy to be defined case by case
7. Pressure (in vacuum chamber)	
> 1,3 hPa	± 15 %
1,3 10^{-3} hPa to 1,3 hPa	± 30 %
< 1,3 10^{-3} hPa	± 80 %
8. Acceleration (steady state) and static load	± 10 %
9. Frequency for mechanical tests	± 2 % (or ±1 Hz whichever is greater)
10. Acoustic noise	± 0,1dB
11. Strain	± 10 %
12. EMC	See ECSS-E-ST-20-07 clause 5.2.1.
13. ESD	See ECSS-E-ST-20-06 See ECSS-E-ST-20-07 clause 5.2.1 for ESD test on space segment equipment.

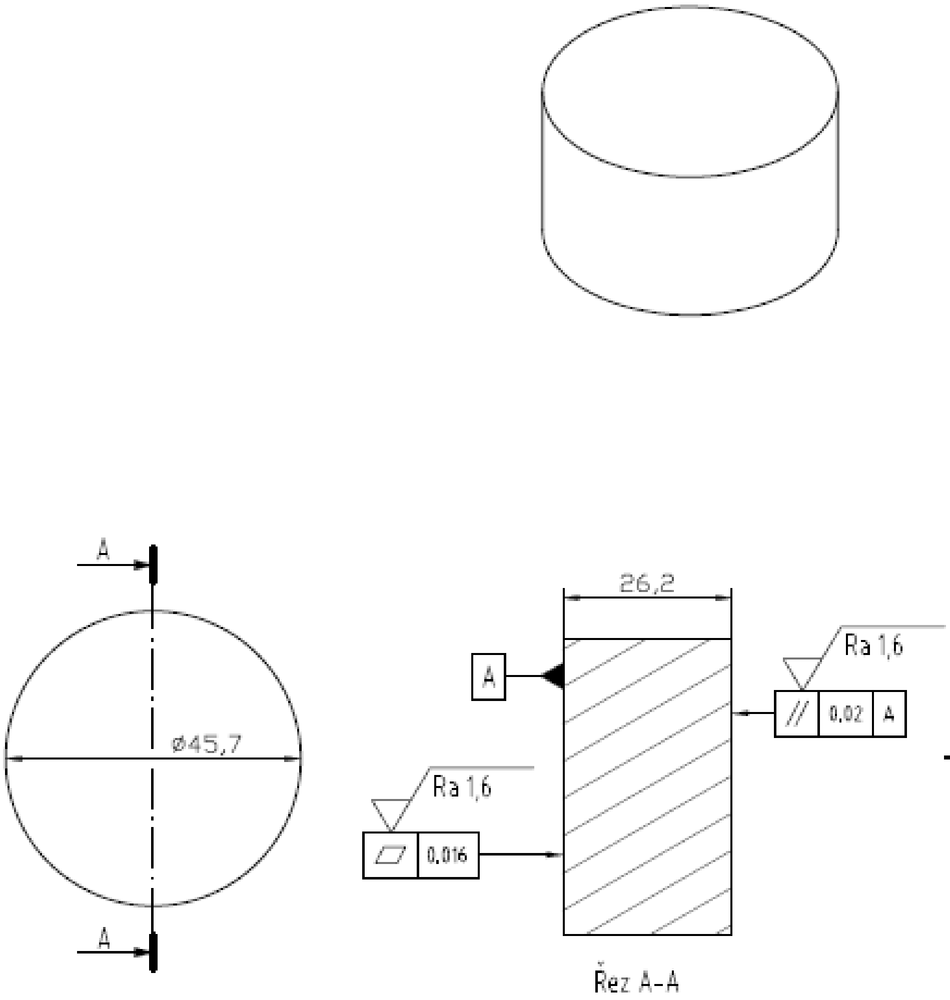
Figure 15.3: *ECSS Standard Test Accuracies.*

APPENDIX A2 – DUMMY V3 DRAWINGS



Struktura povrchu: Ra 3,2	Hrany: +0,3 / ±0,3		Měřítko 1:1	Přesnost ISO 2768-mH Tolerování ISO 8015 Promítání
Materiál CuSn8	Polotovar ø58, t=26,5		Hmotnost - kg	Chráněno podle ISO 16016
LU FSI VUT BRNO	Druh dokumentu VÝKRES SOUČÁSTI		Název DUMMY V3/01 (CLOSED)	
	Kreslil VÁCLAV LAZAR			
	Schválil		Číslo dokumentu 4-LU/MHS-DUMM-V3/01-A	
	Datum vydání 2019-03-13		List /	


Ra 1,6
0,016
Ø 0.06 A
Ra 1,6
0,02 A
A
6
R2
R5
3x120°
Ø4
Ø45,7
3xØ3,2
Ø49
Ø56
2
2
Ø10
3
3
2
2
26,2
Řez A-A
Struktura povrchu:
Ra 3,2
Hrany:
+0,3
+0,3
Měřítko
1:1
Přesnost ISO 2768-mH
Tolerování ISO 8015
Promítání
Materiál CuSn8
Polotovar Ø58, t=26,5
Hmotnost - kg
Chráněno podle ISO 16016
LU FSI
VUT
BRNO
Druh dokumentu VÝKRES SOUČÁSTI
Kreslil VÁCLAV LAZAR
Schválil
Datum vydání 2019-03-13
Název
DUMMY V3/02 (MEAN)
Číslo dokumentu
4-LU/MHS-DUMM-V3/02-A
List /



Struktura povrchu: Ra 3,2	Hrany: +0,3 +0,3	Měřítko 1:1	Přesnost ISO 2768-mH Tolerování ISO 8015 Promítání
Materiál Duratron (Torlon) 4203L	Polotovar ⌀46, t=26,5	Hmotnost - kg	Chráněno podle ISO 16016
LU FSI VUT BRNO	Druh dokumentu VÝKRES SOUČÁSTI Kreslil VÁCLAV LAZAR Schválil Datum vydání 2019-03-13	Název DUMMY V3/03 (OPEN) Číslo dokumentu 4-LU/MHS-DUMM-V3/03-A List /	

APPENDIX A3 – V3 CLOSED & MEAN CATIA MODELS

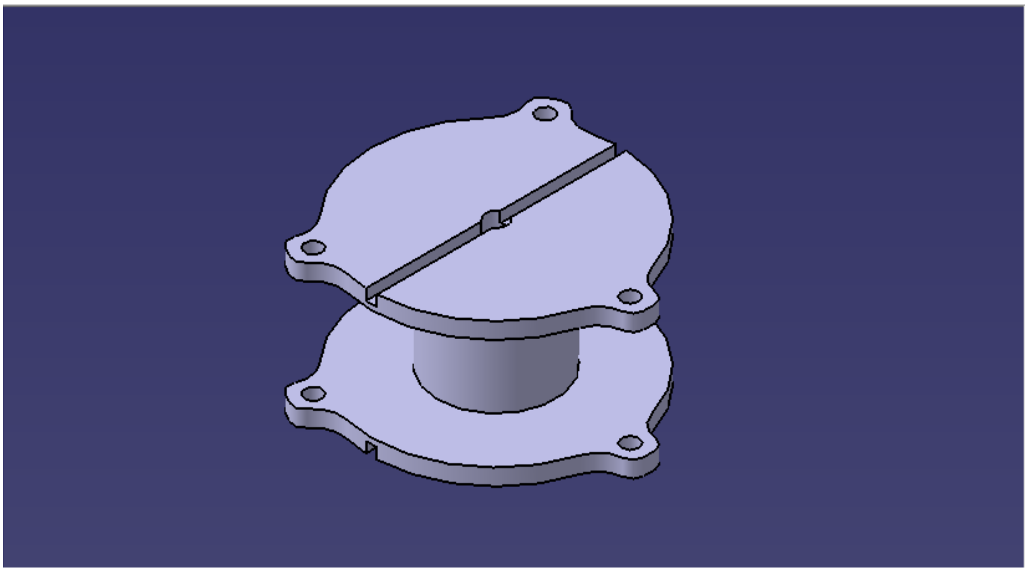


Figure 15.5: *CATIA model – V3 Dummy Closed.*

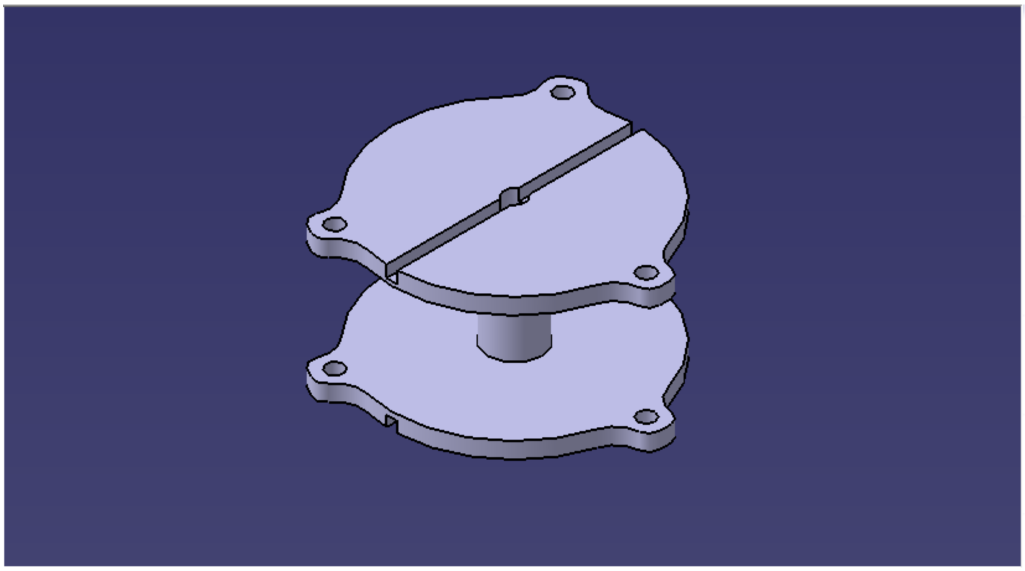


Figure 15.4: *CATIA model – V3 Dummy Mean.*

APENDIX A4 – THERMAL MODEL UI

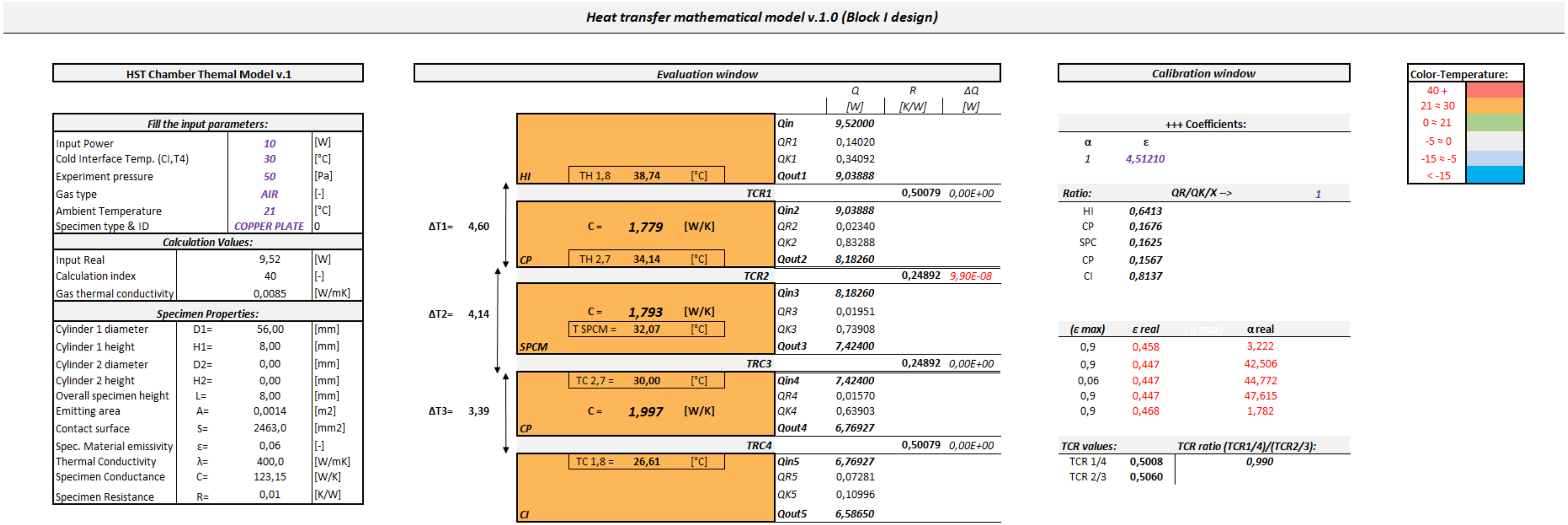


Figure 15.6: *Thermal Model tab, v1.0, User Interface.*

APPENDIX A5 – PHOTO DOCUMENTATION

Figure 15.8: *HST Chamber V3 with later low horizontal WRG position.*

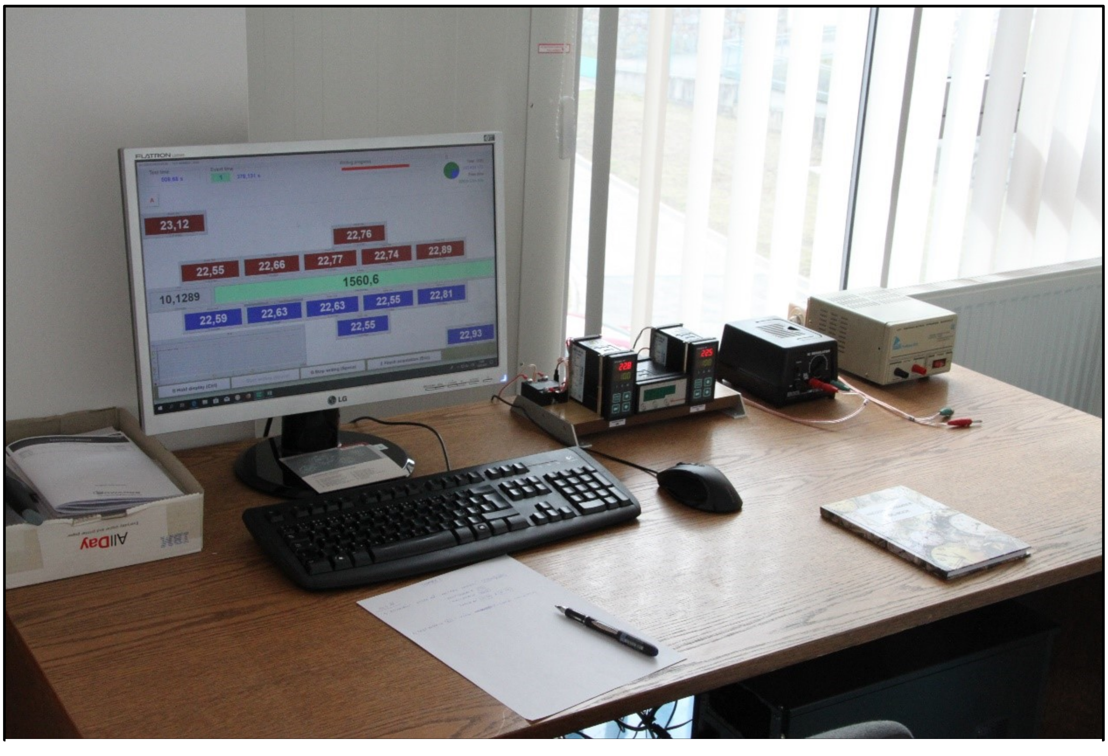


Figure 15.7: *Cleanroom workplace. Both HI & CI Power sources and temperature controllers can be found on the table. PC runs ESAM desktop application.*

Figure 15.10: *HST Chamber V3 initial cleaning and assembling.*

Figure 15.9: *CI thermal insulation process. Two holes on in the flange identifies HST Chamber Version 3.*

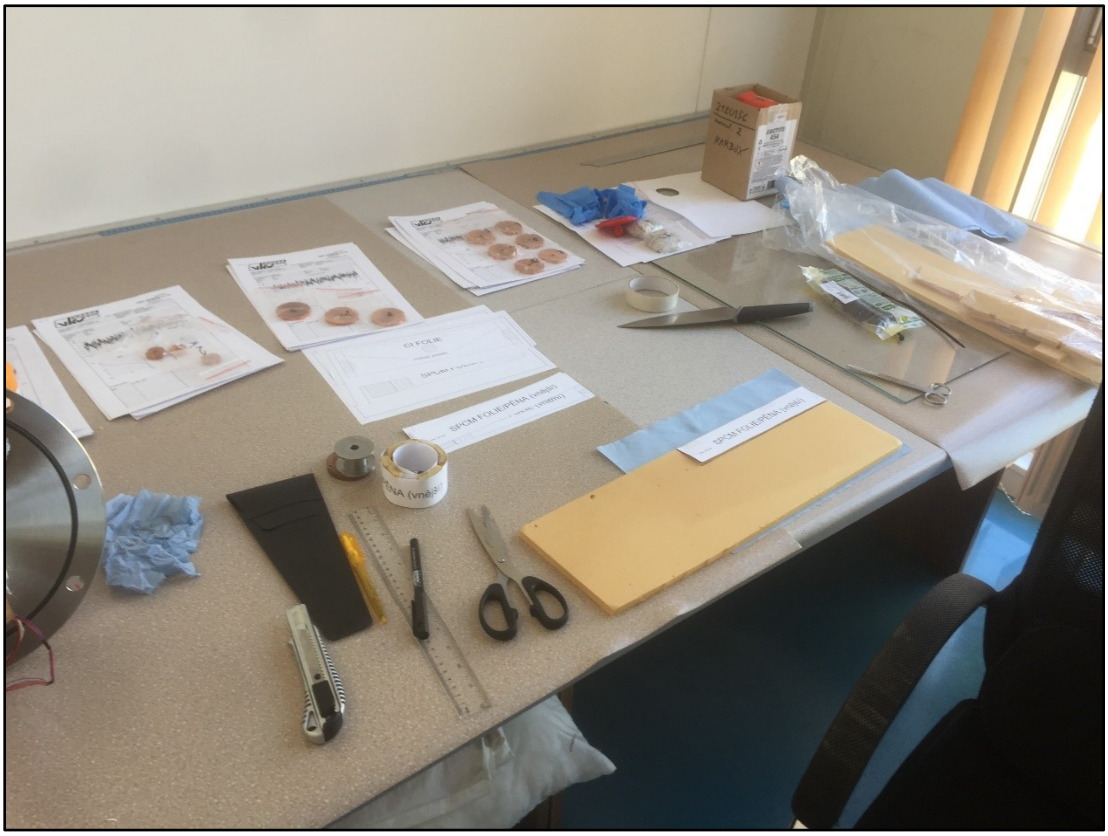


Figure 15.12: *Upilex foam cutting during the thermal insulation preparation.*

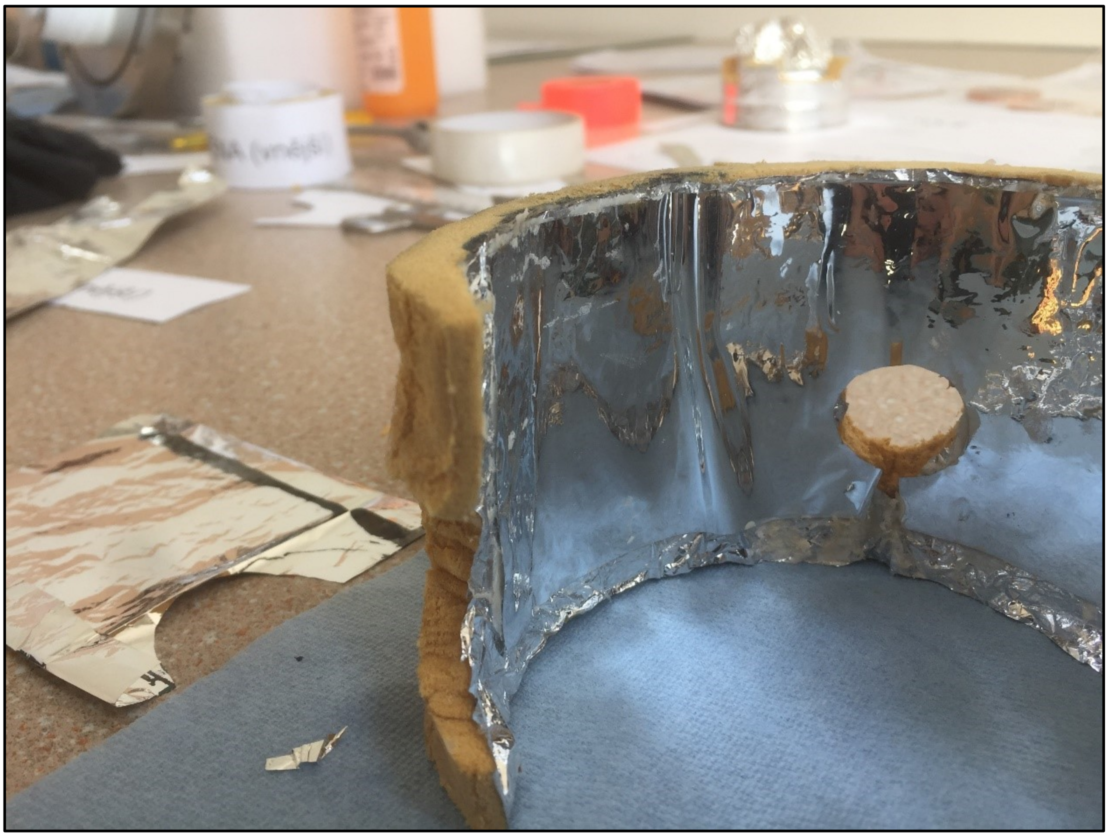


Figure 15.11: *Inner CI thermal insulation view. The layers applied are: Upilex foil, Mylar foil, Upilex foam, and Mylar foil.*

Figure 15.14: *Final CI Thermal insulation. The PTFR white tape is applied on the CI rod. The aluminized Mylar foil can be observed as an outer insulation coating.*

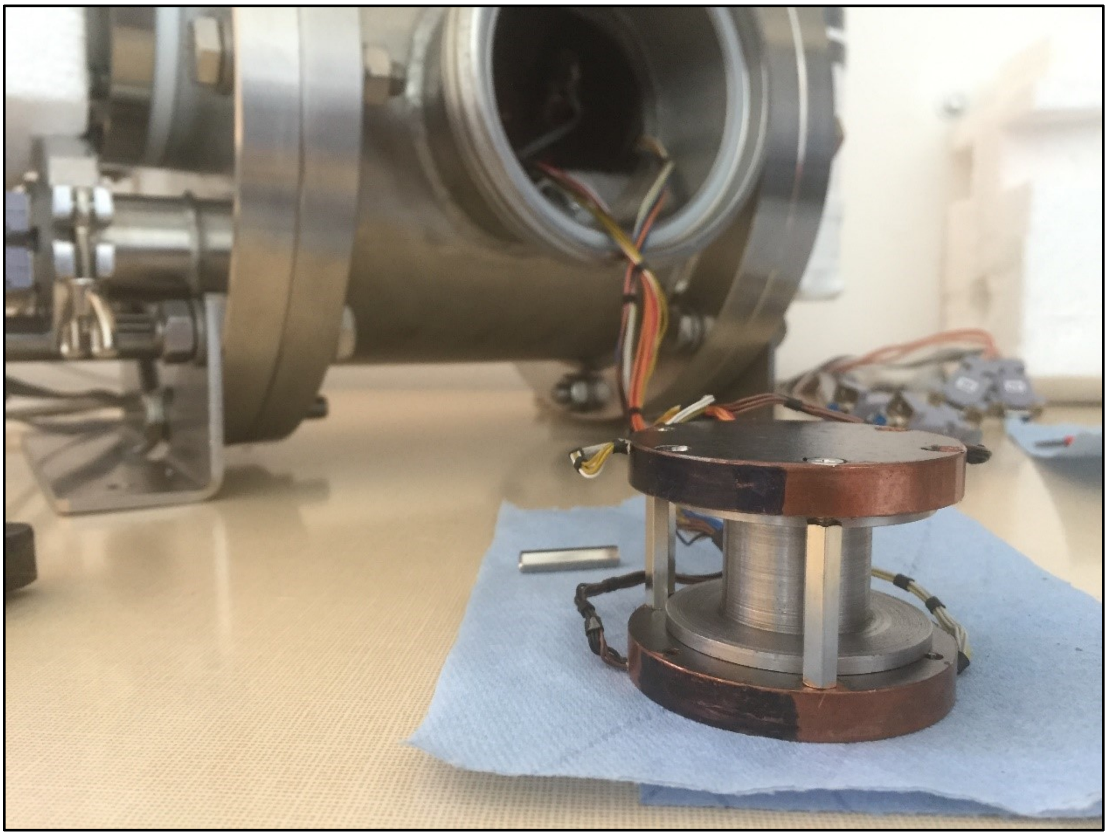


Figure 15.13: *Steel Dummy II place in between hot & cold Copper plates during the initial HST Chamber Version 3 Thermal tests.*

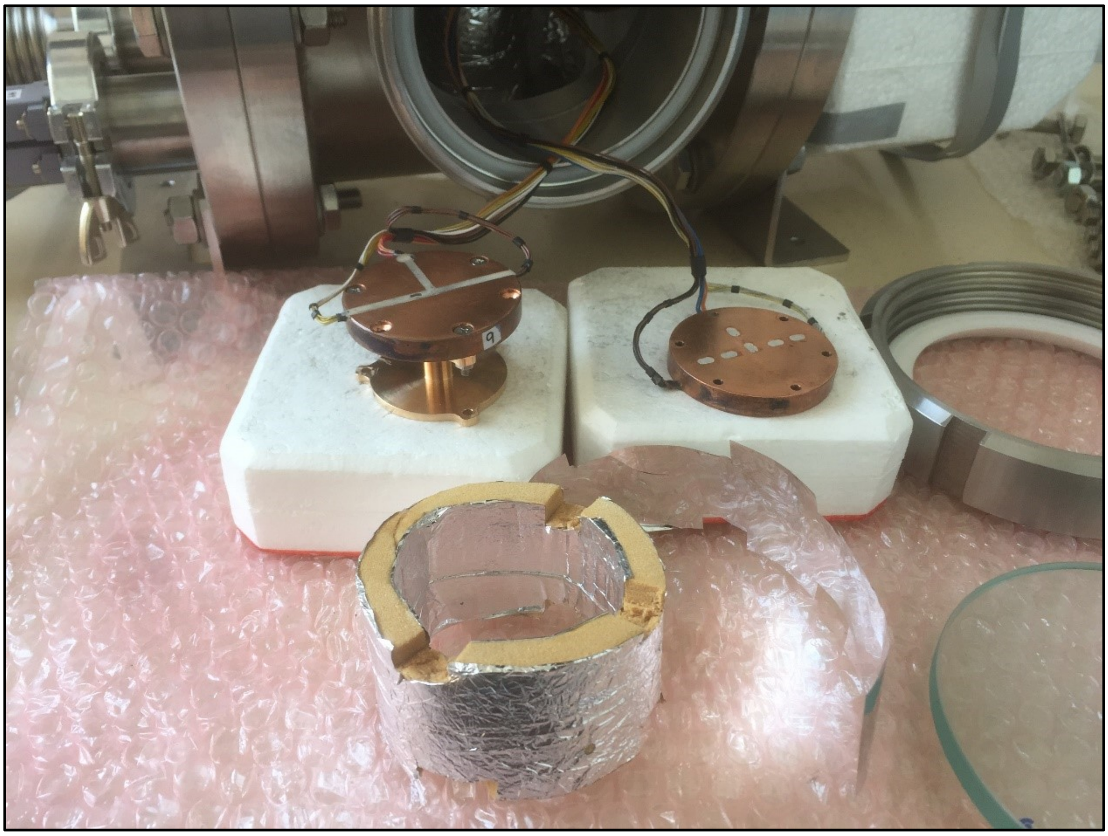


Figure 15.16: *The V3 Dummy Mean specimen exchange. Hot Copper plate is screwed with the specimen through the dummy pads. Final specimen´s insulation coating can be observed as well.*

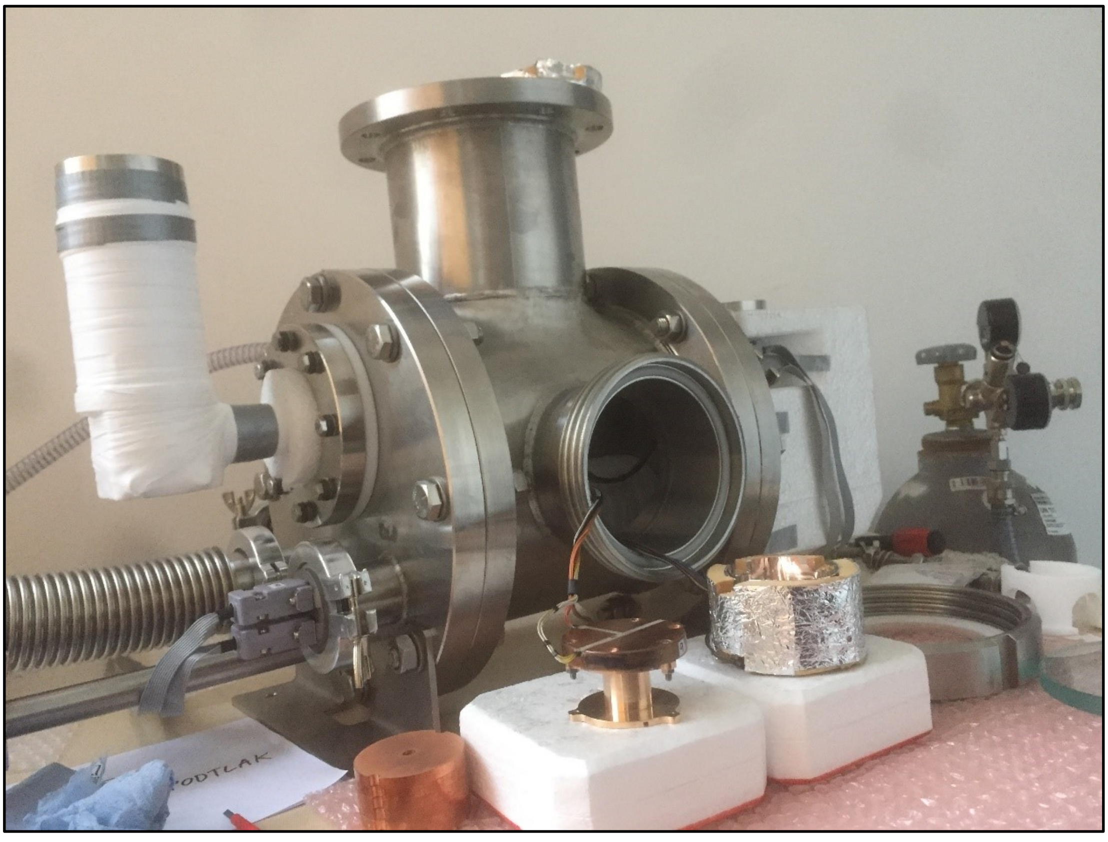


Figure 15.15: *V3 Dummy Closed specimen exchange. Top flange & Inspection window are removed to gain access into chamber during the specimen exchange process.*